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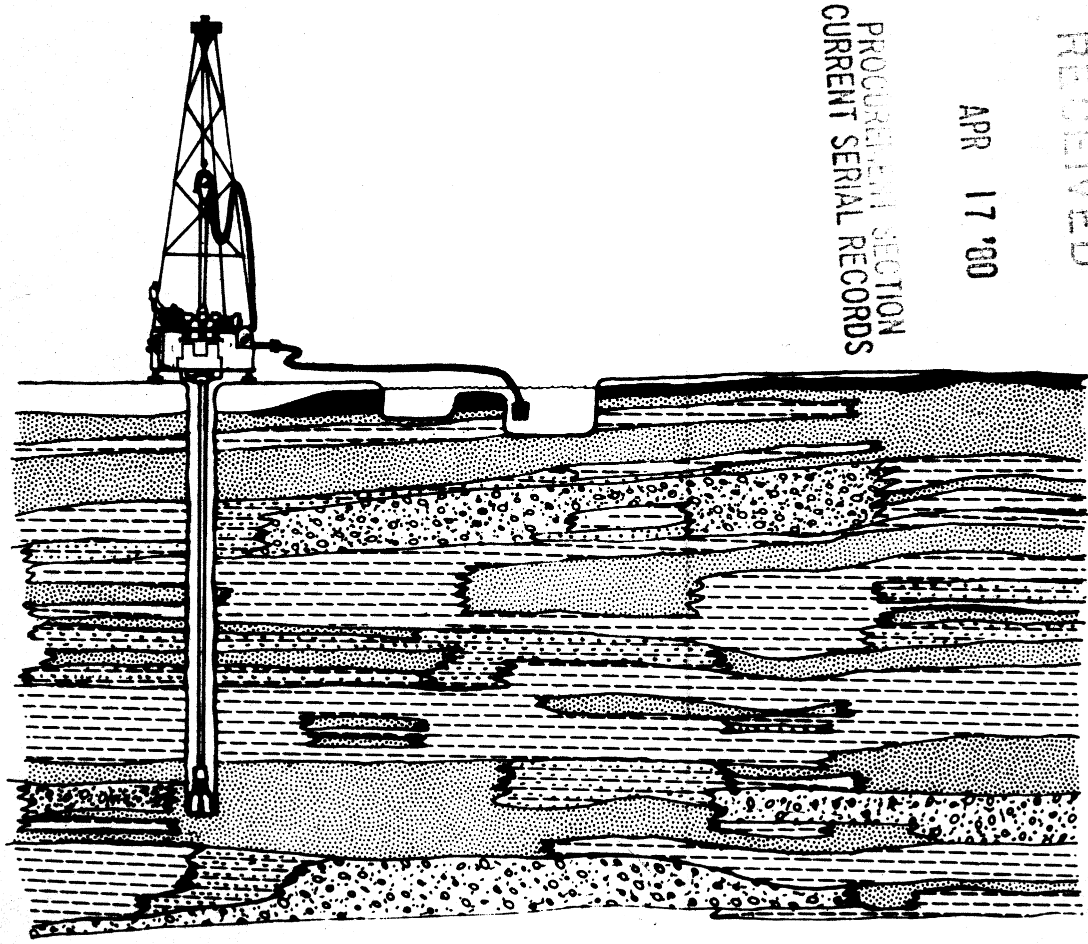
A GEOLOGIC APPROACH TO ARTIFICIAL RECHARGE SITE SELECTION IN THE FRESNO-CLOVIS AREA, CALIFORNIA



UNITED STATES DEPARTMENT OF AGRICULTURE

TECHNICAL BULLETIN NUMBER 1604

PREPARED BY
SCIENCE AND EDUCATION ADMINISTRATION

A GEOLOGIC APPROACH TO ARTIFICIAL RECHARGE SITE SELECTION IN THE FRESNO-CLOVIS AREA, CALIFORNIA

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ABSTRACT

Cehrs, David, Stephen Soenke, and William C. Bianchi. A Geologic Approach to Artificial Recharge Site Selection in the Fresno–Clovis Area, California. U.S. Department of Agriculture, Technical Bulletin No. 1604, 73 pp., 1979.

This paper presents a methodology for using surface and subsurface sedimentary geology to identify and locate recharge sites in alluvial sediments. Computer averaging and plotting of water well logs aided in the demarcation of the subsurface geology. Sitings of both ponded (basin) recharge and well injection recharge are included. Two subsequent chapters expand upon the use of computer averaged water well data for hydrologic investigations and the alluvial geology and related hydrology of the Fresno–Clovis area, California.

KEYWORDS: Alluvial fans, Alluvial sediments, Artificial recharge, Aquifers, Basin recharge, Computers, Fresno–Clovis area (California), Geohydrology, Ground water, Ground water management, Hydrology, Recharge, Sedimentary depositional environments, Surface and subsurface alluvial geology.

PREFACE

Throughout the arid West, water is becoming a more visible, recognized, and volatile commodity as the demands on it become greater. These demands are increasing from both the agricultural and urban sectors. Because the amount of water is finite, the need for the total management of the water we do have increases in direct proportion to the demand. Within this scheme of water management, ground water can, and will, play an ever-increasing role. The concept of cyclic storage of water in subsurface aquifers will be a major tenent of this scheme. In years of plentiful surface water, the excess will be stored underground in the water table, but in years of drought this stored water will be available for irrigation and municipal uses. This paper deals with a methodology for efficiently siting the necessary recharge basins and wells.

In areas of alluvial sediments, the potential for the recharge of surface waters varies with the characteristics of the sediments and the total amount of area exposed to rechargeable water. The techniques discussed in this paper are designed to expedite efficient recharge either in active stream channels or in areas currently devoid of water. This is accomplished by picking the best available geologic sites with easy access to rechargeable water and which are hydraulically, as distinct from topographically, above the area of need. By using cursory survey techniques on geologic and soils maps, initial areas with good surface recharge potentials can be identified. Computer averaged water well logs can be used to delineate the subsurface. This subsurface data, used in conjunction with the surface material data, will demarcate the best potential areas for basins. Some areas with poor surface potential may have excellent subsurface recharge potential and be excellent sites for recharge wells. In all potential sites located by these survey techniques, several exploratory holes should be drilled and sampled, and the hydraulic properties of subsurface layers should be thoroughly checked out. The final siting decision should thus be based on the hydraulic data, as the recharge efficiency and its economic criteria are controlled by the percolation rates of the surface and subsurface strata.

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Issued January 1980

A Geologic Approach to Artificial Recharge Site Selection in the Fresno-Clovis Area, California

By David Cehrs, Stephen Soenke, and William C. Bianchi[1]

INTRODUCTION

This publication outlines an approach for artificial recharge site selection and shows the place of recharged waters in ground water basin management. The first chapter deals exclusively with the specifics of site selection, whereas the following two chapters expand upon and explain some of the specifics mentioned and alluded to in the first chapter.

For an organization interested in initiating a program of artificial recharge, chapter one will be of primary concern as it contains the "how to's" involved. Chapter two will show how subsurface data can be acquired, compiled, and displayed with the intent of increasing the efficiency of site selection and the recharge process. Chapter three is a detailed description of the geology encountered in the Fresno area and how it influences and affects artificially recharged water as well as ground water dynamics. This geologic knowledge may not be of general interest, but it does play an important roll in recharge and ground water movement in alluvial aquifers.

Water consumption in the United States is on the increase for both municipal-industrial and agricultural uses, doubling from 1950 to 1975, and it is expected to double again by the year 2000 (*57*).[2] Today, 22 percent of all consumed water in the United States is ground water, and it appears from economic, quantity, and quality standpoints that our reliance on ground water will increase, though probably not to the point reached by Germany, which obtains 65 percent of its consumed water from below ground (*57*). Today, "the ground-water reservoir in the San Joaquin Valley . . . provides about one-quarter of all water pumped from wells in the U.S.," which exceeds 50 million acre-ft per year (*57*). Fresno, the largest city in the San Joaquin Valley, has the second highest per capita metropolitan consumption of ground water (table 1). It is the 12th largest U.S. metropolitan area whose water system is based solely on ground water (table 2) and is the only major metropolitan area that does not treat its water supply, regardless of water source (*63*).

Subsurface water can be polluted just as easily as surface water but is harder to detect and nearly impossible to clean up. Some of the sources of pollution in Fresno and the San Joaquin Valley are from septic tanks, urban wastewater disposal, sewage lines (*60*), industrial and agricultural process wastes, and agricultural chemicals applied to the Valley's many orchards, vineyards, and cultivated crops. Artificial recharge can reduce and, in some cases, negate the need for well water purification. In Fresno's case, recharged water from the Leaky Acres Recharge Facility, which would have to be treated if consumed directly from the surface source, has actually improved the already remarkably good quality, by world standards, of the ground water (*51*), thus eliminating any need to treat the water at all and still easily exceeding Environmental Protection Agency

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[1] Geologists and soil scientist, respectively, U.S. Department of Agriculture (USDA), Science and Education Administration (SEA), Agricultural Research (AR), Water Management Research Laboratory, Fresno, Calif. 93726.

[2] Italic numbers in parentheses refer to Literature Cited, p. 71.

TABLE 1.—*City ranking based on gallons of water consumed per capita per day. (From Todd (63))*

City	Population	Water used	Per capita use	Source[1]
	Thousands	*Million gallons/day*	*Gallons/day*	
1. Spokane, Wash.	183	68.0	372	G.
2. Fresno, Calif.	150	53.4	356	G.
3. Savannah, Ga.	170	55.0	324	S, G.
4. Tacoma, Wash.	165	48.2	292	S, G.
5. Sacramento, Calif.	181	47.5	262	S, G.
6. Philadelphia, Pa.	2,003	510	255	S.
7. Buffalo, N.Y.	593	145	245	S.
8. Erie, Pa.	160	38.0	238	S.
9. St. Louis, Miss.	760	181	238	S.
10. Corpus Christi, Tex.	212	48.1	227	S.
11. Salt Lake, Utah	272	59.3	218	S, G.
12. Rochester, N.Y.	292	62.9	215	S.
13. Denver, Colo.	620	131	211	S.
14. Omaha, Neb.	327	64.5	197	S.
15. Cleveland, Ohio	1,675	319	190	S.
16. Phoenix, Ariz.	487	92.7	190	S, G.
17. Los Angeles, Calif.	2,458	466	190	S, G.
18. Miami, Fla.	550	102	185	G.
19. Lincoln, Nebr.	128	23.6	184	G.
20. Syracuse, N.Y.	235	42.3	180	S.

[1] G = ground water, S = surface water.

TABLE 2.—*Major cities that rely wholly upon ground water and types of water treatment used. (From Todd (63))*

City	Population	Treatment[1]
	Thousands	
1. San Antonio, Tex.	603	Cl.
2. Miami, Fla.	550	C, Cl, F.
3. Honolulu, Hawaii	405	Cl.
4. Dayton, Ohio	320	C, Cl.
5. Wichita, Kans.	255	C, Cl.
6. St. Petersburg, Fla.	250	C, Cl.
7. Jacksonville, Fla.	247	Cl.
8. Tucson, Ariz.	232	Cl.
9. Albuquerque, N.M.	201	Cl.
10. Spokane, Wash.	183	Cl.
11. Baton Rouge, La.	152	Cl.
12. Fresno, Calif.	150	None.
13. Amarillo, Tex.	150	Cl.
14. Montgomery, Ala.	148	C, Cl.
15. Madison, Wis.	135	Cl.
16. South Bend, Ind.	133	Cl.
17. Lubbock, Tex.	133	Cl.
18. Rockford, Ill.	132	Cl.
19. Lincoln, Nebr.	128	C, Cl.

[1] C = clarification, Cl = chlorinization, F = fluorinization.

water quality criteria. Thus, recharge with high quality water becomes an economically viable alternative (table 3) to water treatment procedures on surface waters (table 4). This is particularly important in chemical removal (table 5) to maintain or improve the quality of ground water. Recharge also helps to stabilize or raise the water table, thus decreasing the pumping lifts, energy, pump size, and cost per unit volume of water pumped.

As an approximation, Fresno, with a population exceeding 190,000 in 1976, consumes approximately 68,000 acre-ft (8383 ha-m) of water per year. If Fresno were able to recharge 68,000 acre-ft of water a year at $4.50 per acre-ft ($306,000) and pay $660,000 in electric pumping bills (as it did in 1976), it would have cost $966,000 in that year for recharged water delivered to mains. On the other hand, if Fresno were to chlorinate and clarify 68,000 acre-ft of surface delivered water (tables 4 and 5), it would have cost $665,000 for chlorination, $4,432,000 for clarification, plus electric pump costs to maintain the present water pressure, which in

1974 were 36 percent of Fresno's actual metered power, and would equal $238,000 for a total of $5,335,000 to supply surface water to the mains. Currently, approximately 14,000 acre-ft (1726 ha-m) of water is artificially recharged a year in Fresno; the rest, 54,000 acre-ft (6657 ha-m), is overdrafted from the aquifer, and the water table shows this.

TABLE 3.—*World project recharge costs, 1971 (58)*[1]

Country	Annual recharge	Capital costs	Operations
	Thousands of acre-feet	*Dollars/ acre-foot*	*Dollars/ acre-foot*
Germany	4	678	197
England	—	12–111	12
France	8	370	62
Do.	12	62	12
Iran	—	—	99
Japan	—	—	1,230
Morocco	—	1,230	123
Netherlands	—	3,700	308
Switzerland	—	247	37
U.S.A. (generalized)	—	62–148	1–12
Leaky Acres[2]	12	41–64	[3] 3.50–4.50

[1] Total capital costs over annual water recharge.

[2] 1972–1975 seasonal average recharge (9).

[3] Exclusive of water costs.

TABLE 4.—*Projected costs*[1] *of drinking water treatment processes. (From the Texas Department of Health Resources (33))*

Process	Costs per 100 people[2]			Costs per 5,000 people[3]			Costs per 100,000 people[4]		
	Dol./ 1,000 gal	*Dol./ capita*	*Dol./ household*	*Dol./ 1,000 gal*	*Dol./ capita*	*Dol./ household*	*Dol./ 1,000 gal*	*Dol./ capita*	*Dol./ household*
Chlorination	0.05	2.16	6.72	0.03	1.76	5.52	0.03	1.79	5.72
Clarification	1.32	52.51	163.31	.30	16.87	52.46	.20	12.62	39.25
Ion exchange	2.27	90.19	280.49	.55	30.80	95.80	.20	13.00	40.43
Activated alumina	.19	7.79	24.23	.08	4.58	14.24	.05	3.18	9.89
Activated carbon	1.18	46.90	145.86	.19	10.97	34.10	.04	2.44	7.59
pH control	.02	.61	1.87	.006	.35	1.08	.003	.02	.07
Total	5.03	200.16	622.48	1.156	65.35	203.20	.523	33.05	101.75

[1] Assumes 7 percent interest on capital costs amortized over 15 years plus operation and maintenance costs.

[2] Assumes 109 gal (0.412 m^3) produced per person per day.

[3] Assumes 154 gal (0.582 m^3) produced per person per day.

[4] Assumes 174 gal (0.658 m^3) produced per person per day.

TABLE 5.—*Estimated capital investment costs for fluoride and nitrate removal (33)*[1]

Population served	Fluoride removal by activated alumina: Cost per system	Fluoride removal by activated alumina: Minimum cost per person	Nitrate removal by reverse osmosis: Cost per system	Nitrate removal by reverse osmosis: Minimum cost per person	Nitrate removal by ion exchange: Cost per system	Nitrate removal by ion exchange: Minimum cost per person
	Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
25–99	2,600	26	30,000	303	41,000	414
100–499	6,100	12	52,500	105	68,000	136
500–999	12,000	12	99,650	100	100,000	100
1,000–2,499	22,000	9	195,800	78	140,000	56
2,500–4,999	37,000	7	381,500	76	470,000	94
5,000–9,999	60,000	6	726,000	73	810,000	81
10,000–99,999	130,000	1	1,228,500	12	2,000,000	20
Average	38,528	10	290,507	107	518,428	129

[1] Does not include operation and maintenance costs.

Chapter 1.–Use of Geology in Artificial Recharge Site Selection

INTRODUCTION

The conditions required for successful artificial ground water recharge are geologically site specific (that is, successful ponded recharge requires site conditions that allow maximum possible percolation on the smallest surface area). The specific site's surface and subsurface geology and the geology's relationship to the configuration of the ground water basin determine where in the basin the optimum benefit of recharge will be found. Furthermore, today there are no longer extensive areas from which recharge sites may be chosen; the areas are now overlain by valuable agricultural and urban developments, and the cost and ability to acquire land and to access it to rechargeable surface water override the geologic and hydraulic acceptability of the site.

The following discussion will outline a methodology developed for the Fresno interfan to select potential artificial recharge sites. Fresno, which resides on a complex system of alluvial fan deposits originating from multiple sources, does not represent a universal sedimentary regime; therefore, this site selection program will require alteration to fit the specific geologic conditions and hydraulic parameters encountered in other parts of the United States or the world. The basic evaluation process, however, should be applicable. Two types of recharge will be addressed here: (1) Basin recharge or water spreading and (2) injection well recharge of both shallow and deep types. Each has its own applications to the specific surface and subsurface geology of a site or area. Where there are permeable surface and subsurface profiles, the ponding method may be employed, but where subsurface impermeable or semipermeable perching horizons limit surface percolation and preclude ponding, deep well injection systems might be used. Both systems require permeable deeper aquifers to transmit the water away from the recharge facility.

SITE GEOLOGY DICTATES RECHARGE METHOD

Basin Recharge

SURFACE PARAMETERS

Surface geology viewed in terms of soil permeabilities is important in recharge; soil hydraulic parameters at or near the surface (0 to 3 m) will determine whether a site is suitable for surface recharge or deep well recharge. Where one sedimentary depositional mode has existed for prolonged periods of time, the surface geology is useful in interpreting the subsurface sedimentary deposits, especially their vertical and lateral extents, because the surface deposits ultimately form aquifers, aquicludes, and aquitards.

High permeabilities are needed in near-surface sediments for basin recharge. There are several possible ways of identifying these areas geologically or from soil surveys. Figures 2 and 3 (also see chapters 2 and 3) are of the same area to the northeast of Fresno and Clovis, Calif. (fig. 1). Figure 2 is a geologic map showing the

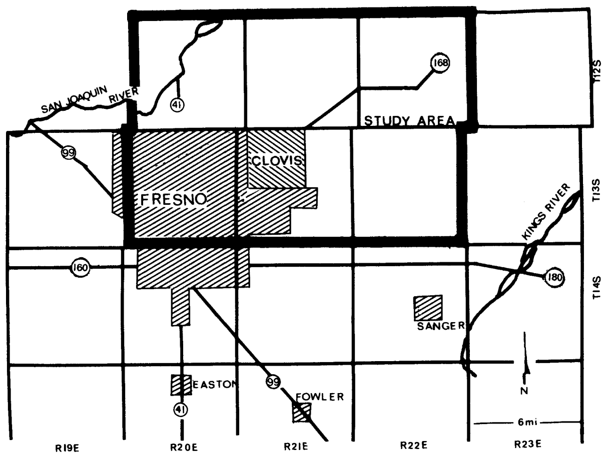

FIGURE 1.—The Fresno–Clovis metropolitan-agricultural area outlining the six townships in which this study was conducted. Population centers are shaded.

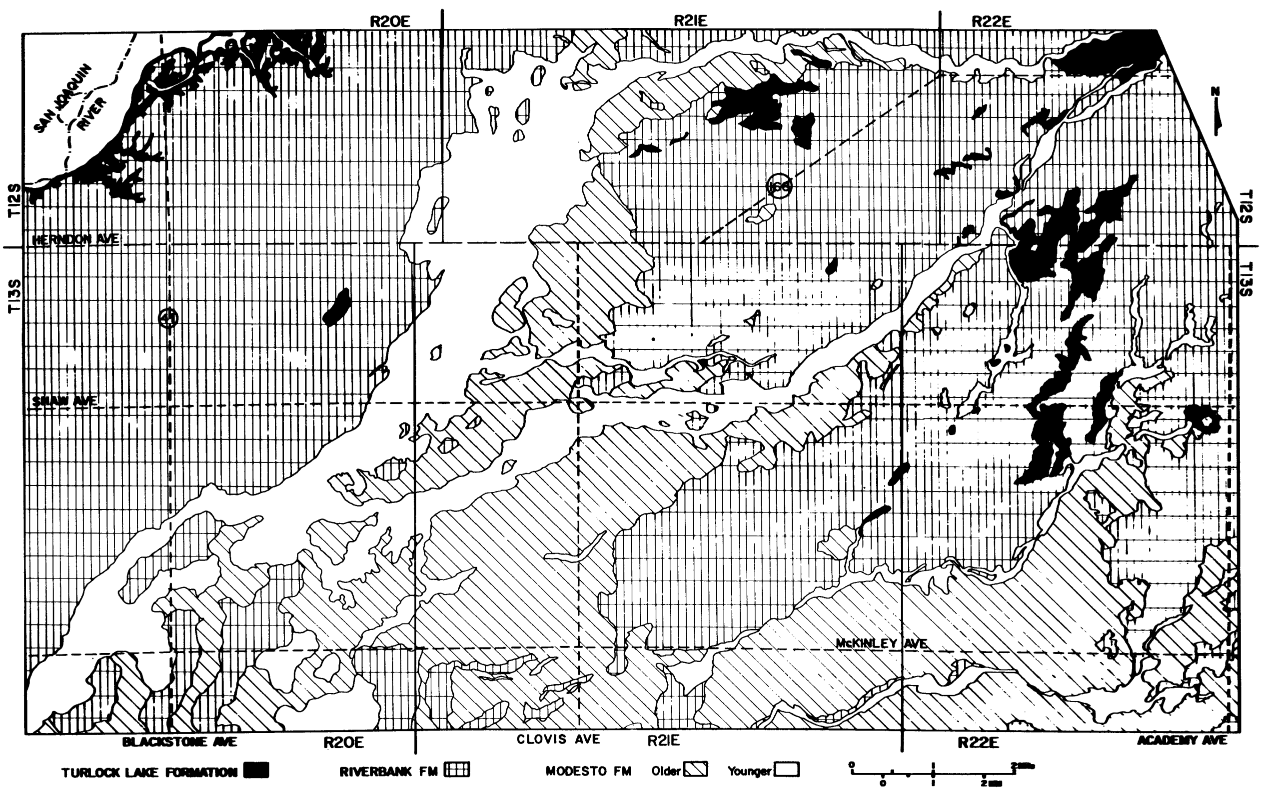

FIGURE 2.—Geologic map of the area northeast of the Fresno–Clovis area, Calif. The Modesto Formation sediments include the most desirable basin recharge sites.

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three surficial formational units and their distributions; figure 3 shows soil permeabilities and their distributions.

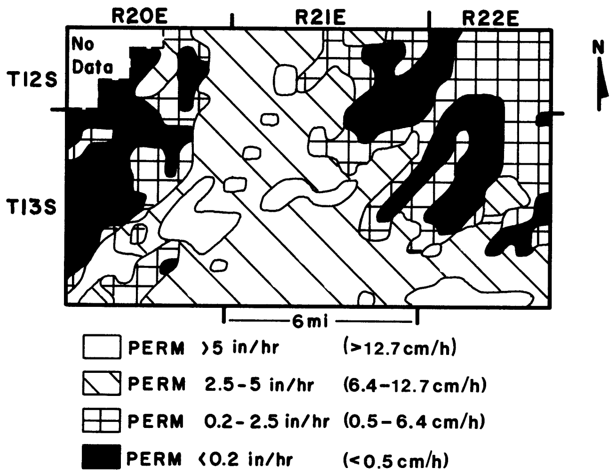

FIGURE 3.—Soil permeabilities (after Nightingale, personal commun.) to the northeast of the Fresno–Clovis area, Calif. (see fig. 1). Permeabilities greater than 5 in/h (12.7 cm/hr) are associated with Modesto Formation sediments.

Geologic groupings.—The Modesto Formation sediments, the youngest in the Fresno alluvial sequence, are the most permeable. The Younger Modesto, principally stream channel and channel associated sediments (channel lags, levees, and crevasse splays), consist of sands with variable amounts of included finer silts and clays. They are the most permeable surface sediments, and therefore the most desirable for surface recharge sites. The Older Modesto sediments, also associated with stream channels, are sandy, but due to the incorporation of floodflow silts and clays are less permeable than the Younger Modesto; they constitute the second best sedimentary unit for recharge.

The Riverbank Formation, which is older than the Modesto Formation, presents a problem in recharge and to agriculture in the Fresno area in that a "B" horizon hardpan (varying from iron silica to carbonate cement) is associated with its upper surface (fig. 4 and chapter 2). This hardpan, which is not inclusive, is the first perching horizon encountered in the alluvial sequence beneath Fresno. If water is ponded directly on hardpan soils, recharge is only significant where there is enough total hydraulic head pressure (depth of ponded water) to overcome its low permeability or, if the structure of the hardpan soil is physically altered, by ripping operations.

Several things can be done to circumvent the perching properties of the hardpan. Water recharged through the overlying sequence of Younger and Older Modesto Formation sediments developes an added 3 and 5 m of head when it perches on the hardpan horizon and thus can override some of the reduced permeability effects. This has occurred at the city of Fresno's Leaky Acres Recharge Facility (fig. 5) where a deeper perching layer (at 10 to 12 m) ultimately controls the vertical movement of recharge water, and the hardpan (4 m deep) restricts flow only until the perched mound from the 10-m layer reaches the hardpan (fig. 6). The hardpan thickness varies, and, in some locales, it is possible to excavate through it into more permeable sediments, which may be at least 3 to 4.5 m thick, thus circumventing the perching horizon.

Regardless of the hardpan, the Riverbank Formation, as a unit, is not as consistently permeable in the Fresno area. More overbank and flood plain associated sediments (more fine-grained included sediments) are exposed on the fans, thus the Riverbank is a less desirable unit on which to place a surface recharge project.

The third and oldest exposed local formation is the Turlock Lake Formation. Its small outcrops generally are topographic highs in proximal (upper, near source) fan locales. Many outcrops have surface or near-surface gravels, which may be cemented. All of these parameters precluded recharge in surficial Turlock Lake Formation sediments.

In summary, an understanding of recharge is enhanced by knowledge of the depositional system with which you are dealing (alluvial, deltaic, flood plain, marine, glacial, or eolian), the sediments provenance (source area and rock types), where the different grain sizes and sortings and bedding features occur, and which sediments are most conducive to recharge. A knowledge of the surface sediments is also useful in estimating and interpreting the subsurface and its recharge potential.

Soils groupings.—A second method of analyz-

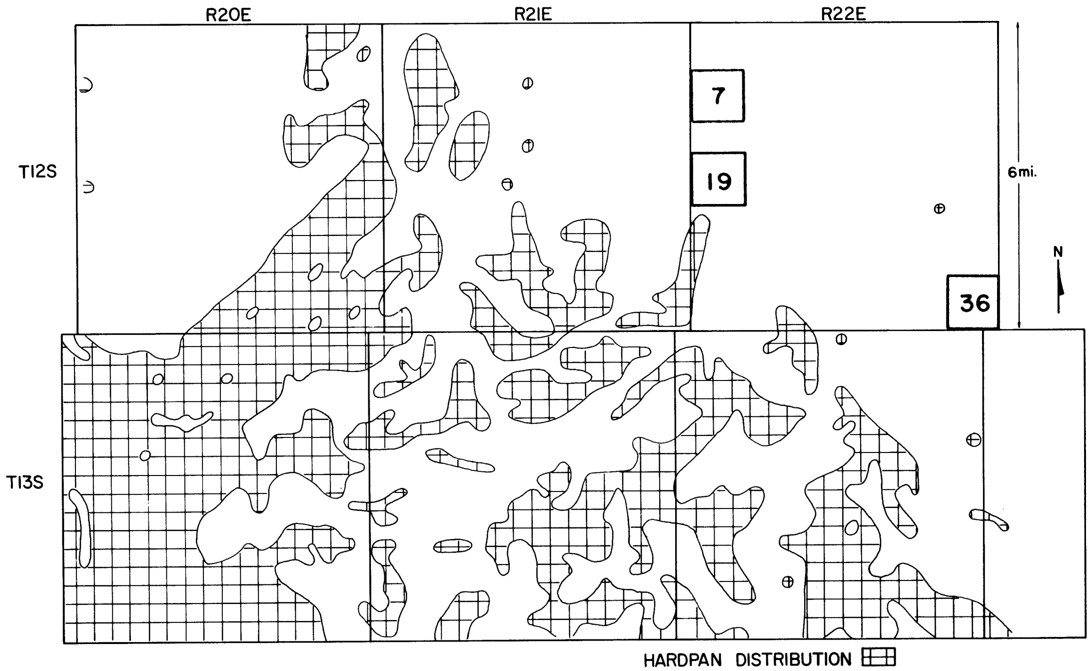

FIGURE 4.—The hardpan distribution in the northeast Fresno–Clovis, Calif., area. The hardpan is the first restrictive layer in the local alluvial sequence and may be at or near the surface (0 to 5 m deep). Surficial exposures are associated with the Riverbank Formation.

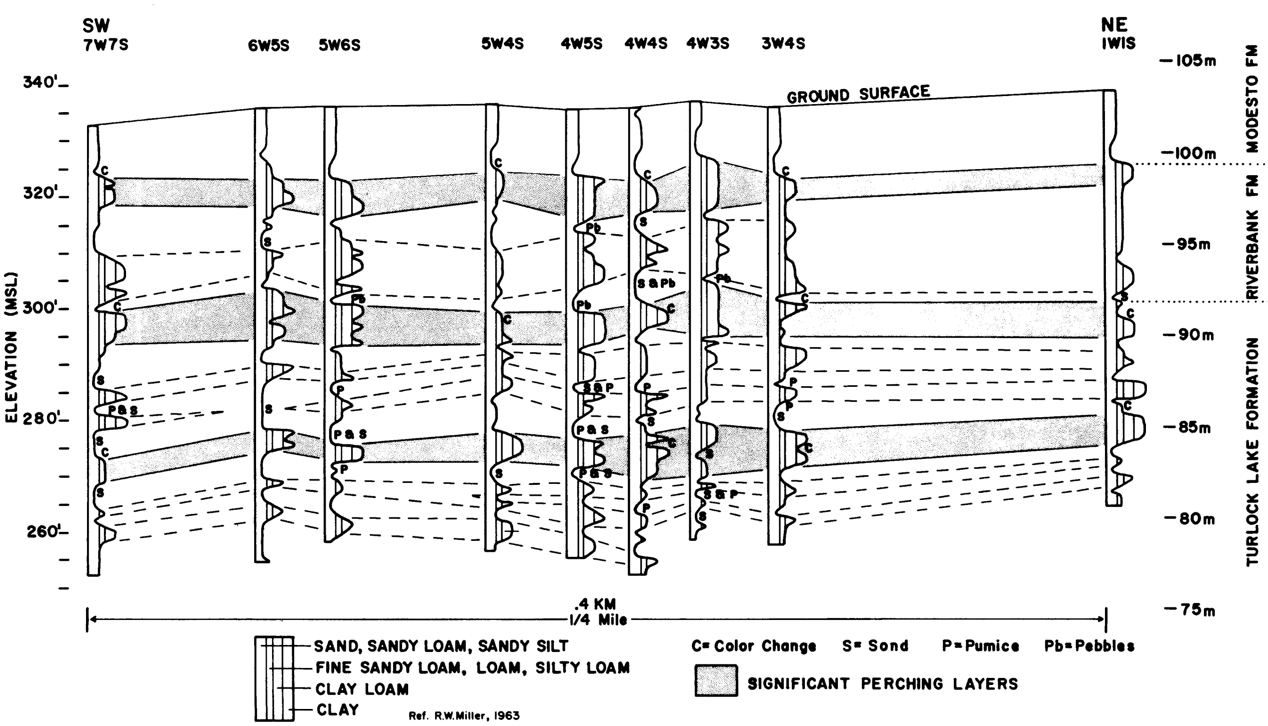

FIGURE 5.—Stratigraphic and lithologic (*48*) cross section beneath the Leaky Acres Recharge Facility in Fresno, Calif. The first perching layer is the equivalent of the surficial Riverbank Formation hardpan. The third perching layer ultimately controls the percolation rate of the recharge facility (see fig. 6).

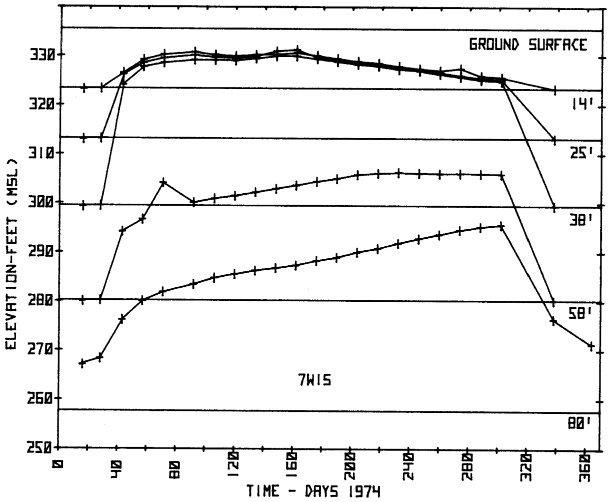

FIGURE 6.—A hydrograph from station 7W1S at the Leaky Acres Recharge Facility during the 1974 recharge season. After the initiation of recharge, the three upper piezometers (14, 25, and 38 ft) have coincident piezometric surfaces, which act as a unit indicating their hydraulic continuity. The head loss between the 38- and 58-ft piezometers, due to the intervening restrictive layer (layer 3 in fig. 5), is significant as it marks a break in the aquifers hydraulic properties. At Leaky Acres, this layer actually controls the downward percolation and recharge rate of the facility.

ing the surface sediments uses soil characteristics as mapped in many areas of the United States by the U.S. Department of Agriculture's Soil Conservation Service (SCS). They not only physically classify soils as to texture and structure but also give some indication of their permeability (table 6). Figure 7 (Nightingale, personal commun.), taken from SCS soil map data (*37*), was analyzed with respect to its permeability, based on SCS estimates. Figure 3, which is a portion of this larger map, closely resembles the geologic map of the area (fig. 2). The areas of greatest permeability (PERM ⩾ 5.0 in/h; ⩾ 12.7 cm/h) are associated with areas of Younger Modesto stream channel sediments. Similarly, the areas of PERM 0.2 to 2.5 (0.5 to 6.4 cm/h) and ⩽ 0.2 in/h (⩽ .05 cm/h), those least applicable to recharge, are associated with Riverbank and Turlock Lake Formation sediments. In the PERM 2.5 to 5.0 in/h (6.4 to 12.7 cm/h) category, permeabilities and formational units which are acceptable to recharge, overlap. This intermediate PERM group comprises both Riverbank and Older Modesto sediments. Part of this formational-soil permeability overlap is due to the more permeable surficial cover (up to 1.3 m

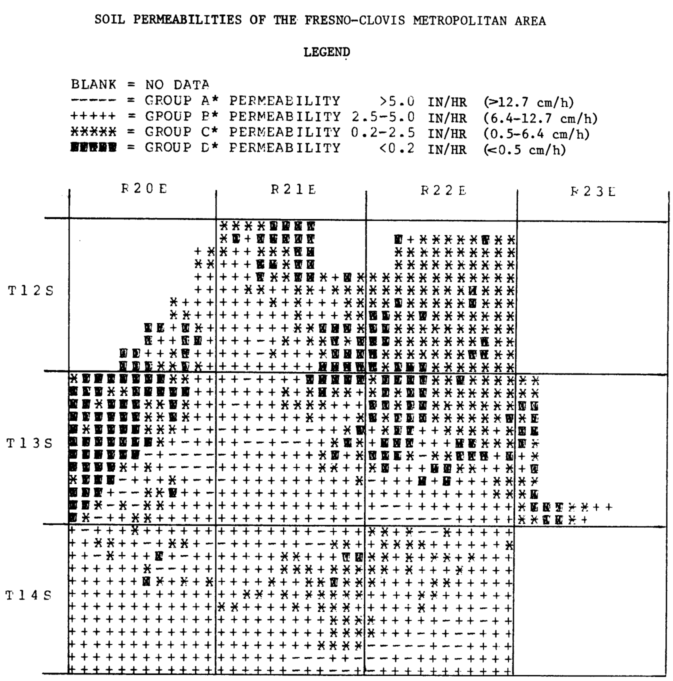

FIGURE 7.—Permeabilities compiled according to their hydrologic soil group assignment, using an area weighted mean based on the soil series in a quarter section.

deep) of Riverbank sediments above the less permeable Riverbank hardpan.

In the Fresno area, therefore, it is necessary to know the distribution of the hardpan and the formational units with respect to the surface permeabilities. That is, merely looking at the surface soils texturally does not adequately identify recharge sites because of this overlap in soil and geologic units. The Modesto Formation soil units span a textural range in which the following textures predominate:

MODESTO FORMATION SOILS

Younger	Older
Loamy sand	Loamy sand
Coarse sandy loam	Coarse sandy loam
Sandy loam	Sandy loam
Fine sandy loam	

The Riverbank sediments include a finer range of soil types; some have hardpans beneath them (0.6 to 2 m from the surface) while others have a hard substratum (incomplete hardpan) or weakly cemented units beneath, all of which tend to impede water percolation:

RIVERBANK FORMATION SOILS

Sandy loam
Sandy loam, hard substratum
Sandy loam, shallow
Loam
Loam, hard substratum
Loam, shallow
Clay

The Turlock Lake Formation soils are exposed on the upper fan surface and thus have coarser textures, including gravels within 1.3 m of the surface. Some of these soils also exhibit hardpans within 1 meter of the surface, but the hardpans are not nearly as predominant as they are in the Riverbank soils:

TURLOCK LAKE FORMATION SOILS

Sandy loam
Loam

The descriptive approach involves a soils grouping based on SCS soil-type names and their geologic formation affinities. Table 6 gives such an association for Fresno. This breakdown is based (1) on the knowledge of the particular depositional system that operates locally and how it naturally changes with time, (2) the patterns that individual soil outcrops form, and (3) their relationship to the regional depositional pattern. This type of soil grouping is responsible for much of the geologic delineation of figure 2, the geologic map of the area. Thus, similar conclusions may be arrived at using some soil characteristics and geologic parameters to define recharge sites, but in the long run it is a blending of the geologic setting with the soil characteristics (permeabilities) that can best be used in identifying acceptable surface sites for ponded recharge areas. Besides sedimentary constraints, economics and access must also be considered in locating surface recharge sites (*9*). The most difficult constraint to overcome is probably that of finding and acquiring a piece of property that has access to surface water. This is becoming harder with time as expanding urbanization and agriculture drive the price of land up or completely remove it from possible recharge uses by building and development. If an appropriate piece of land for recharge is found but remote

TABLE 6.—*Soil series associated with the Tertiary and Quaternary formations of the Fresno area, and their glacial relationships. (After Janda (*39*) and Marchand (*44*))*

Rock stratigraphic unit Name (age)	Pedologic units (soil series (*37*))
Recent alluvium (Holocene)	Riverwash, Dello, Foster, Grangeville, Greenfield, Hanford, Honcut, Tujunga.
Modesto Formation, Upper member (Late Wisconsin)	Atwater, Delhi, Grangeville, Greenfield, Hanford, Hesperia, Merced, Pachappa, Tujunga, Visalia.
Lower member (Early and Middle Wisconsin)	Atwater, Borden, Fresno, Greenfield.
Riverbank Formation (Illinoian?)	Academy, Alamo, Centerville, Chualar, Exeter, Madera, Porterville, Ramona, San Joaquin, Yokohl.
Turlock Lake Formation (Kansan? and Nebraskan?)	Cometa, Friant Pumice, Montpellier, Polasky, Rocklin.

from any water access, the cost of installing a pipeline or canal may èxclude the site. Another condition contingent upon cost effectiveness is the possibility of excavating a near-surface, less permeable horizon (in Fresno's case, the hardpan) to expose more permeable sediments beneath, thus increasing the recharge of the basin. In the long run, these access and economic constraints will play a bigger role in the acquisition of recharge sites as the finances of water management are scrutinized and controlled more closely.

SUBSURFACE GEOLOGIC PARAMETERS

The subsurface geology is important for several reasons in surface recharge methods. For horizontal dispersal of recharge water, you must have the least flow restrictive profile (that is, one with the fewest perching layers) and the best lateral subsurface aquifer continuities. If surface hardpans of excessive thickness or near-surface soil impermeability negate efficient economic surface recharge, then deep-well injection sites may be located in suitable areas based on deeper sedimentary profiles and aquifer properties and continuities. It is advantageous to know the regional subsurface depositional geology (how different sediments sizes and sortings were deposited and where they are found) and unit hydraulic response (that is, which depositional units or groups of units will conduct more water in given directions than others). This information is needed to determine where the recharged water will move down gradient or, put another way, where the greatest benefit will be specifically attained within the area.

In defining the subsurface geology, one should first use the data available. In California, a 1948 law requires that for all water wells drilled a record of the sediments penetrated (well driller's log) must be filed with the Department of Water Resources (DWR). These well logs are confidential and available for scrutiny only to the owner of the well, the well driller, and the DWR. Other public agencies requesting such information from the DWR may use it for research if anonymity is maintained.

Many people have a very circumspect opinion of the information available on well logs. There is some validity to this, as not all drillers record accurate logs, whereas others only record sands and clays, disregarding any other type of sedimentary unit; however, when a large enough number of well logs are available, chances are better for an acceptable data base compilation.

To handle the volume of well log data and to have a useable output form (see the following chapter), we reduced and transformed the well logs from a descriptive driller's log to one of estimated specific yield (ESY) for each layer of strata described. These transformed driller's descriptions and their particular depths were then processed and averaged by computer with a data output based on one hypothetical representative well for each quarter-quarter section (16 data points per section with 36 sections per township). This coverage has been more than adequate for the basic purpose of the project—that of searching for general areas of acceptable recharge site parameters. These ESY maps are, in effect, grain size distribution maps defining and outlining the ancient stream channels and their associated coarser sediments at depth.

In looking for surface recharge sites, the first 15 to 18 m of the subsurface should have the best possible hydraulic parameters (permeabilities and transmissivities). Figures 4, 8, and 9 (see chapters 2 and 3) are all computer compiled and averaged data, respectively, for the local hardpan, 0 to 20 ft (0 to 6.1 m) and 0 to 50 ft (0 to 15.2 m) ESY slices of the profile. Using these grain-size distribution (ESY) maps, it is possible to start looking for potential sites that will have maximum permeabilities in the near-surface sediments, for rapid percolation of ponded recharge water, and also have the best possible profile (most permeable) with the least number of aquitards (perching horizons) in the first 15 m, for the best vertical transmission of the recharged water. Ideally, a site should also have adequate horizontal water transmission properties (lateral continuity of the aquifers) to negate any perching effects on the recharge rate. By overlaying the various maps (figs. 4, 8, and 9), comparisons of areas with higher ESY's and no hardpans can be made, thus outlining the vertical sequence at any one locale.

For example, sec. 7 of T. 13 S., R. 21 E. has a high ESY (greater than 20) in the first 20 ft (6.1 m) (fig. 8), which would allow good surface percolation. There is some hardpan (fig. 4), but

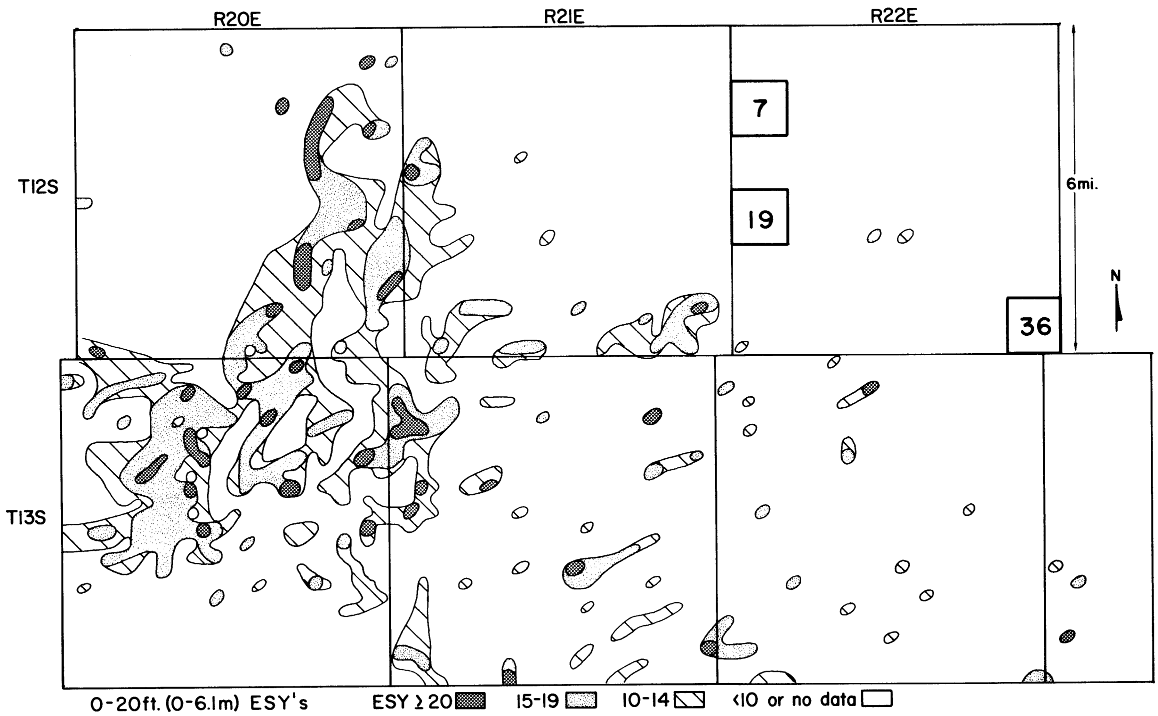

FIGURE 8.—Near-surface (0 to 20 ft, 0 to 6.1 m) estimated specific yields (ESY's) in the Fresno–Clovis area important in basin recharge siting.

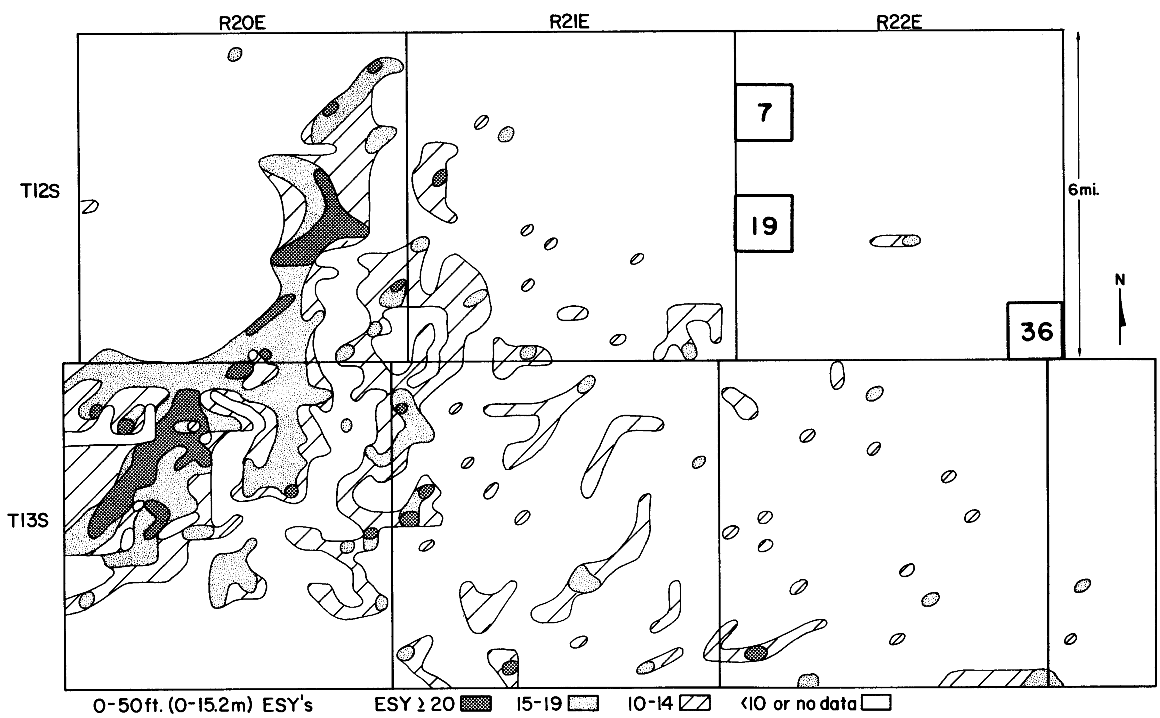

FIGURE 9.—Shallow depth (0 to 50 ft, 0 to 15.2 m) estimated specific yields (ESY's) important in basin recharge siting. San Joaquin River sediments predominate in T. 12 and 13 S., R. 20 E.

it is not continuous throughout the area. There is also a good ESY profile from 0 to 50 ft (0 to 15.2 m) (fig. 9), indicating a smaller possibility of aquitards in this critical interval. This area has good surface properties as it is covered with Youngest Modesto Formation sediments (fig. 2) and also has good surface soil permeabilities (fig. 3). Therefore, this area warrants onsite investigation to confirm its recharge potential.

Another example is sec. 36T, 12 S., R. 21 E. where there are good to moderate ESY's in the first 20 ft (6.1 m) (fig. 8) with decreasing ESY's in the next 30 ft (9.2 m) (as shown on fig. 9), but there are major problems in the surface material. Although the hardpan is more continuous in this area (fig. 4), both the surface geology and soil permeability are restrictive (figs. 2 and 3). This area also has Riverbank Formation sediments at the surface and, therefore, the poorest possible surface soil permeabilities. Here is a site where the subsurface may be adequate for a surface recharge site, but the surface sediments are not. This may be circumvented, however, if the hardpan, which is mainly responsible for the poor permeabilities, is removed. This would require that the hardpan be within an economically feasible distance for excavation and that there be an adequate profile below with no other limiting perching horizons.

Another consideration in a potential recharge site is where the recharged water is going and how it will get there. Figure 10 shows the ground water contours beneath the Fresno–Clovis area. There is a gradual southwesterly gradient in the water surface as it slowly moves to the axis (or trough) of the San Joaquin Valley some 48 to 64 km distant. The water table in the area ranges from 18 to 30 m below the ground surface. The most permeable and transmissive stream channel and channel-related sediments horizontally transmit and direct the majority of the recharged water both above and below the water table at and away from the recharge site. Figure 11 shows how chlorides recharged with water percolated at the Fresno sewer farm tend to follow the near-surface

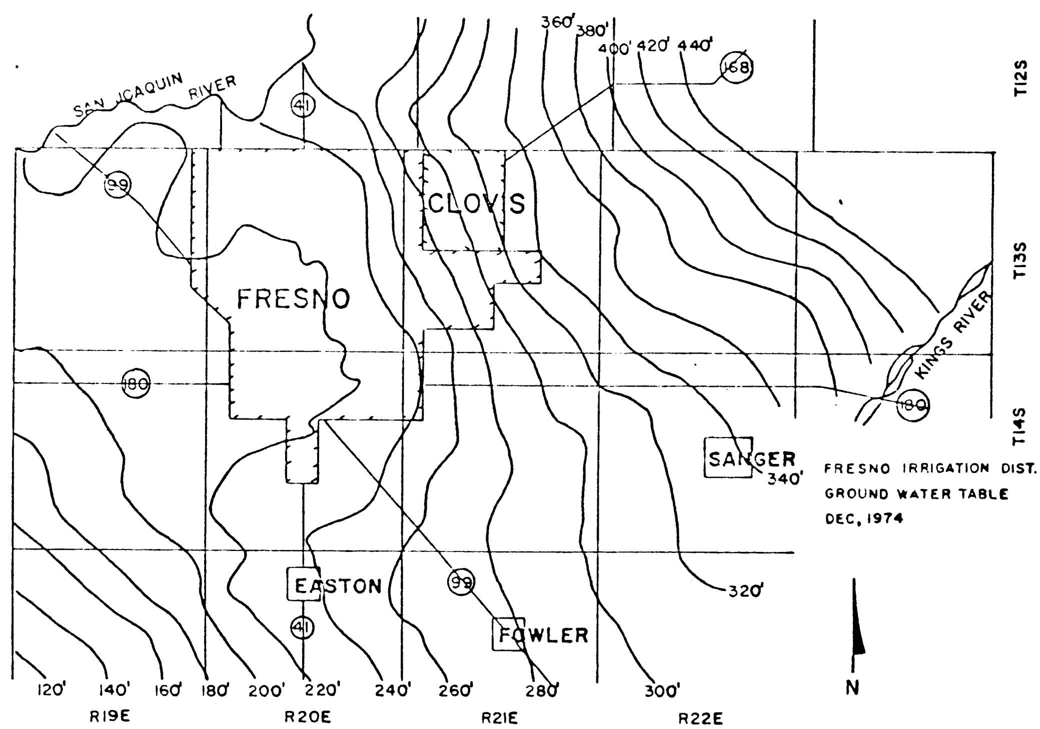

FIGURE 10.—The Fresno–Clovis Metropolitan area water table. The hydraulic gradient generally is perpendicular to the axes of the San Joaquin Valley and the Sierra Nevada foothills.

stream channel sediments (*17*). The transmissive properties of the sediments may be examined by looking at the ESY maps. Figure 12, showing the entire averaged depth of the available well log data (generally to 61 m), gives a good indication of where the recharged water might go when put into perspective with the general hydraulic gradient (fig. 10). The water recharged at sec. 36, T. 12 S., R. 21 E., is associated with ancient (paleo) Dog Creek sediments that continue west-southwest into sec. 19, T. 13 S., R. 22 E. The influence of this recharged water will be more confined and pronounced in this reach of paleochannel sediments, but from sec. 19 downgradient, the recharged water's influence will not be reduced vertically but spread out over a greater area (less of a noticeable effect at any given point). The influence of recharged water from sec. 7, T. 13 S., R. 21 E., would be more immediately dispersed as it has greater continuity with the more highly permeable sediments to the west, and the recharged water's effect will be felt over a greater area but with less of an increase in the water table.

Figure 13 shows the effect from the Leaky Acres recharge area on the water table as reflected in the change of the ground water contours (water table surface) from December 1972 to December 1973. The hydraulic gradient and the effects of recharge are in a southwest direction, but the noticeable increase in the water table of more than 5 ft (1.5 m) is some 6.4 km downgradient from the recharge basin. In Fresno, the zone of influence is not only governed by the locations and continuities of the paleostream channels (high ESY's on the maps), where the recharge site is located, but also by the pumping cone of depression beneath the city's well field (fig. 10).

Once a potential surface recharge site is located, using all the available surface and subsurface data (the geologic, soils, and ESY maps),

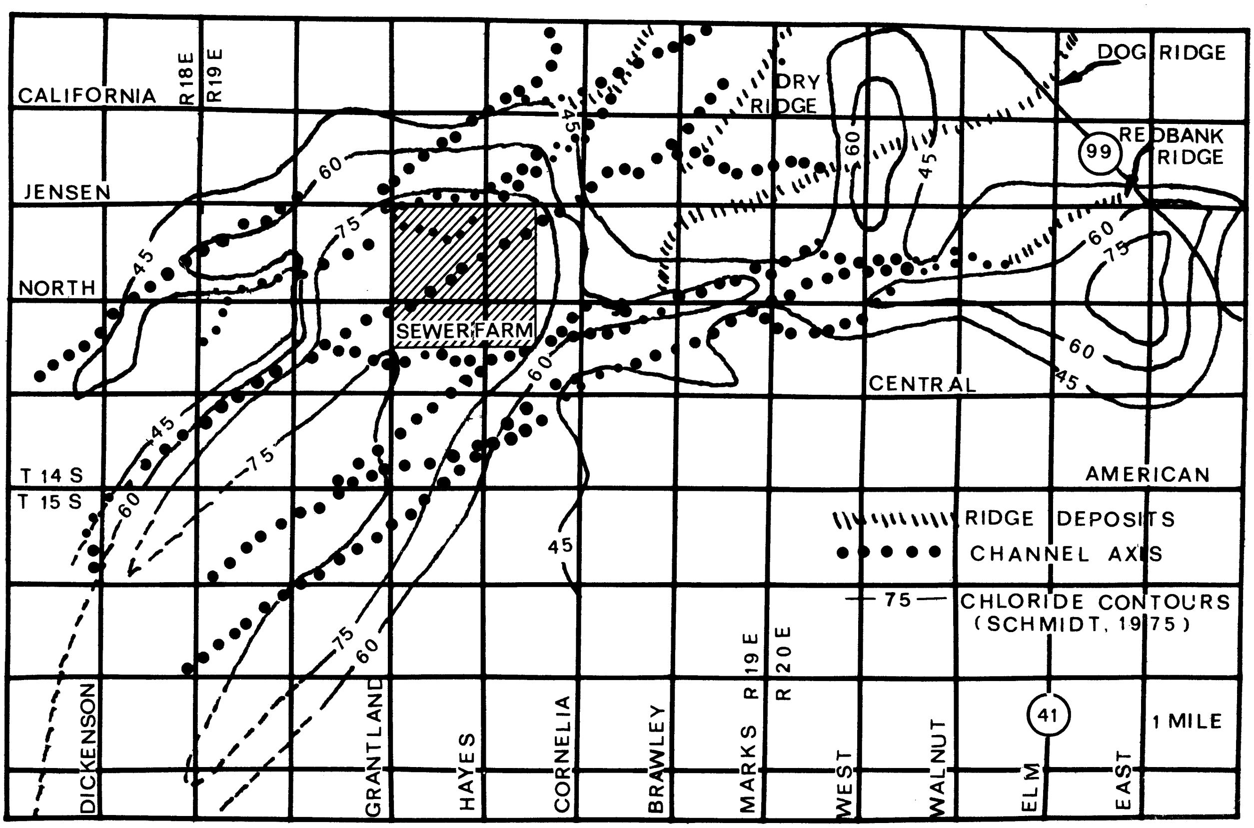

FIGURE 11.—Chlorides, derived from sewer-main leakage and recharge from the sewer farm, follow surficial and near-surface, more permeable and transmissive stream channel sediments.

it is necessary to know if there is land available for recharge development and if there is access to recharge water. If these criteria are met, onsite test drilling should begin.

ONSITE INVESTIGATIONS

Regardless of the size of a potential recharge area, the site should be drilled to acquire a more accurate knowledge of the subsurface conditions than that inferred from preliminary geologic studies. Drill sites should be selected at the corners, midway points on the edges, and, if possible, in the center of the potential recharge site. In our investigations, a mobile, hollow stem auger, drill rig with a small hammer coring device was used (fig. 14). We augered to 60 ft (18.3 m), sampled every 2-1/2 ft (0.75 m), logged the sediments, and kept the core samples for future laboratory sieve analysis. The thicknesses, textures, and colors (for reference correlation) of the aquifer sands and the clay and silt horizons encountered, should be recorded.

Once the drilling is completed, it may be helpful to construct a fence diagram (fig. 15) of the subsurface based upon the drilling logs of the potential site to better delineate the major aquifers and perching layers and their spatial relationships (horizontal and vertical extents). In the Fresno area, multiple perching horizons will be found almost everywhere, but here the goal is to find the locale with (1) the fewest perching horizons—those that are found should be thin and 3 to 4.5 m below the surface (thus increasing the head on that layer)—and (2) the least permeable perching layer (the controlling or limiting horizon) is at a depth greater than 6 m, allowing the perched water to move laterally away from the recharge site.

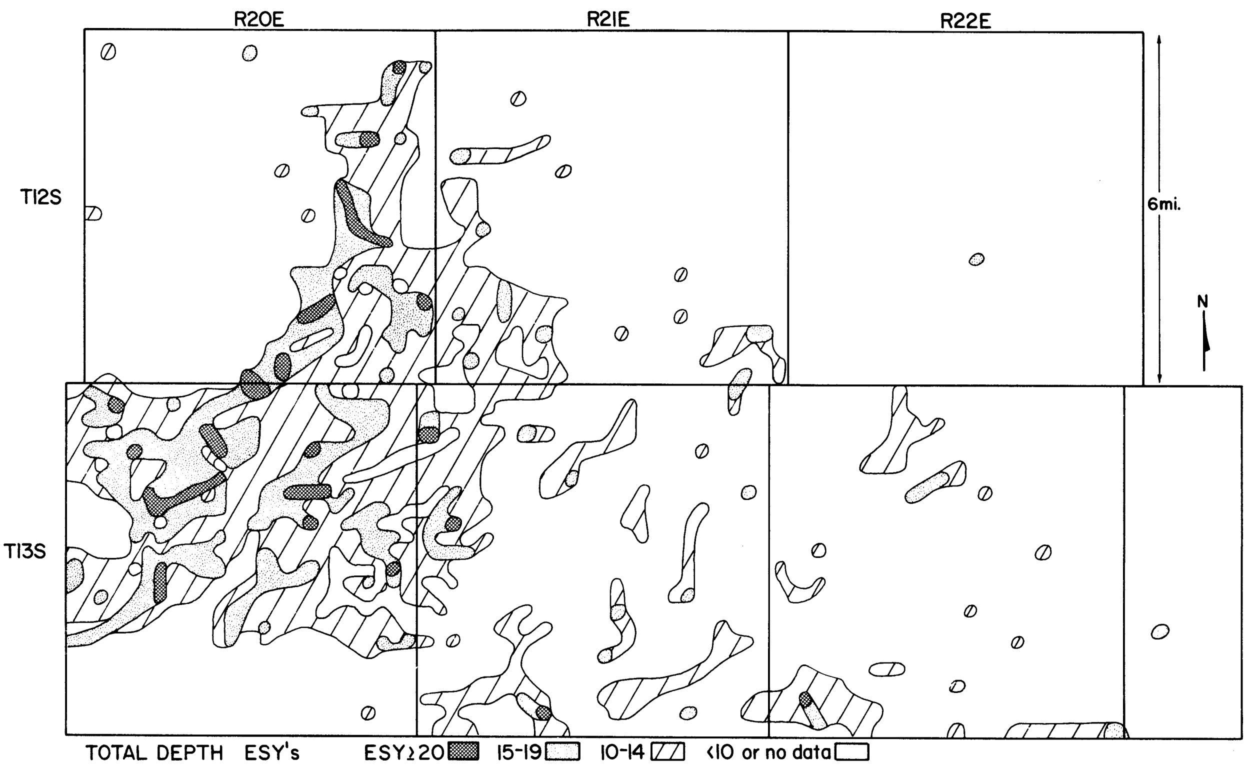

FIGURE 12.—ESY's averaged for the total depth of each quarter-quarter section well log. The diagram is useful for siting both basin and injection well recharge sites and indicates where the best aquifer continuities might be located. The high ESY material in the western portion of the diagram is coarser, ancient San Joaquin River channel sediments.

Injection Well Recharge

For the Fresno fans, injection wells of several types have been tested for artificial recharge of water. Shallow injection shafts (no deeper than 18.3 m (*47*)) and well injection deeper than 30 m (*8*) have been designed and proven successful. In both wells and shafts, the object is to bypass shallow, less permeable or impermeable perching layers, thus providing recharge where surface conditions preclude ponding. Again, ESY computer mapping helps locate potential sites. Similar, but less rigid, physical constraints to the surface recharge sites will have to be met,

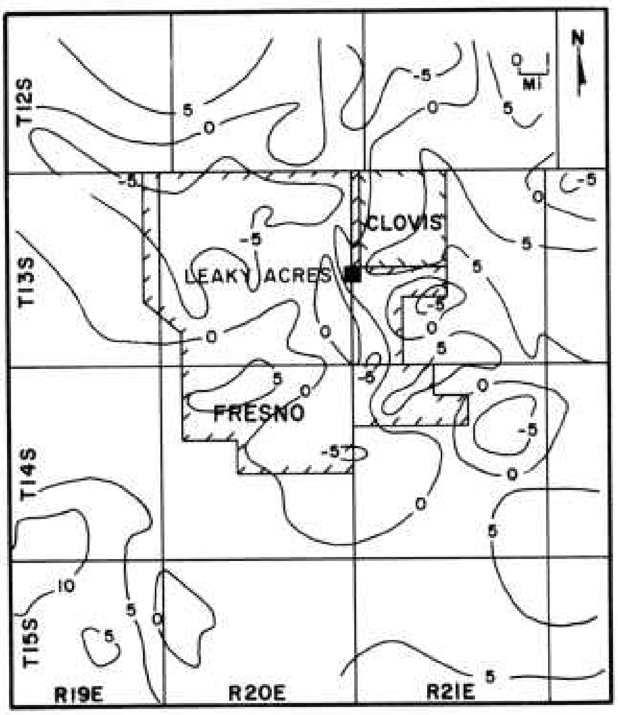

FIGURE 13.—An equal change map (in 5-ft (1.5 m) increments) of the water table, beneath the Fresno–Clovis area, Calif. When compared with the regional water table gradient (fig. 10), the change map shows the positive effect of 1 year's recharge (1972–73) from the Leaky Acres Recharge Facility. This positive effect principally occurs as a 5-ft (1.5 m) increase in the water table in T. 14 S., R. 20 E. Other positive influences to the southeast in T. 14 S., R. 19 E., and T. 15 S., R. 19 E., may be in part due to Leaky Acres. Upgradient, a 5-ft (1.5 m) increase, evident beneath Clovis, is partially due to Leaky Acres, whereas the rest is from agricultural irrigation to the north and east of Clovis.

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FIGURE 14.—Mobile, hollow stem auger, drill rig used for onsite investigation.

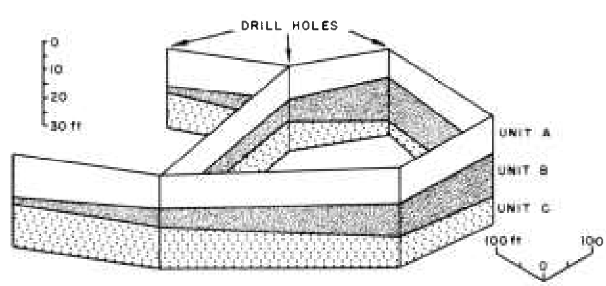


FIGURE 15.—A fence diagram of three hypothetical units, showing their three-dimensional spacing relationships.

such as adequate but much smaller surface area requirements and access to recharge water.

As in surface ponding, the objective of deep well injection systems is to get the maximum amount of recharge water into the system—where it is needed—most efficiently and economically. Knowing the local hydraulic gradient and its relationship to the aquifer system is essential in locating the best possible recharge well site. The reason for this is to identify the general area where the recharge benefit will occur down gradient. The ESY maps, again, basically outline the areas where the ancient stream channels have been in the past. The majority of the recharged water will move through the system of lateral and vertical interconnections of these coarser sediments, influencing not only the water quality (*51*) but also the water table elevation.

An advantage of injection recharge systems is that the wells may be located adjacent to the water supply. Thus, wells may be sited in canals, ditches, streams, and river channels or on their levees, because the space constraints are only limited by problems of equipment size and access to the particular sites picked. Deep well injection may also be effectively sited within surface recharge ponds, as has been done at Leaky Acres in Fresno (*8*), or within a built-up urban area with little open space available.

A major concern involved in efficiently injecting surface water is getting it to a level of quality such that the water and particles will not clog the well. This may be accomplished by treating and filtering the delivered water to get it into chemical and physical equilibrium with that of the aquifers, (that is, no air, biologically pure, and free of suspended solids) so it will not clog the well or the surrounding aquifers (*8*). Another way of handling the problem is to let untreated water clog the well and aquifers and then redevelop the well, removing the clogging agents, so that efficient injection may begin again (*47*).

In both shallow and deep well injection, there is little concern for the surface sedimentary horizons because they are bypassed. In the Fresno area, this means that surficial geologic constraints, soil permeabilities, and hardpan locations are all ignored. The shallow recharge shafts tested thus far were drilled with a 3- to 4-ft (1- to 1.3-m) diameter bucket auger with a 60-ft (18.3 m) capability. Here the 0- to 20- and 0- to 50-ft (0 to 6.1- and 0- to 15.2-m) ESY maps (figs. 8 and 9) are of the greatest interest in locating possible sites. (Choose areas of higher ESY's that have better aquifer continuities (figs. 8, 9, and 11) and are hydraulically upgradient from the area you wish to recharge.)

Deep well recharge in Fresno (*8*) has been accomplished using a 250-ft (76 m) well with the lower 200 ft (61 m) of casing louvered (perforated). Siting these deep recharge wells only requires (1) perusal of the ESY maps through the vertical interval you expect to intercept with the perforated well casing or, conversely, (2) seeing how much aquifer thickness looks acceptable for recharge and basing the perforated depth on this information. This preliminary casing design estimate might change during drilling according to the onsite well log, if it turns out that more or less aquifer material is intersected than expected. In locating a deep well site, the complete set of ESY maps from the total average depth (fig. 11) to the individual 50-ft (15.2 m) slices (figs. 16 and 17) should be inspected. One problem with the deeper ESY maps in the Fresno–Clovis area is that fewer wells are drilled to that particular depth, thus figures 16 and 17 (50 to 150 ft, 15.2 to 45.7 m) have less reliable information on them because of less input data. Once again, the things to consider in locating a well injection site are (1) selecting a location that intercepts the greatest continuous thickness of high ESY material (coarse sediments), (2) making sure the site is hydraulically above the area you would like recharged, and (3) locating a site such that it has as much permeable coarse-grained sedimentary continuity as possible for the immediate transmission and dispersal of the recharge water to the ground water system.

The advantages, objectives, and site constraints of well injection recharge can be summarized as follows:

- Well injection of recharge water bypasses any shallow or near-surface less permeable or impermeable perching or constricting layers or hardpans that would impede the percolation of surface recharged water, thus increasing the efficiency (economically and hydraulically) of recharge.

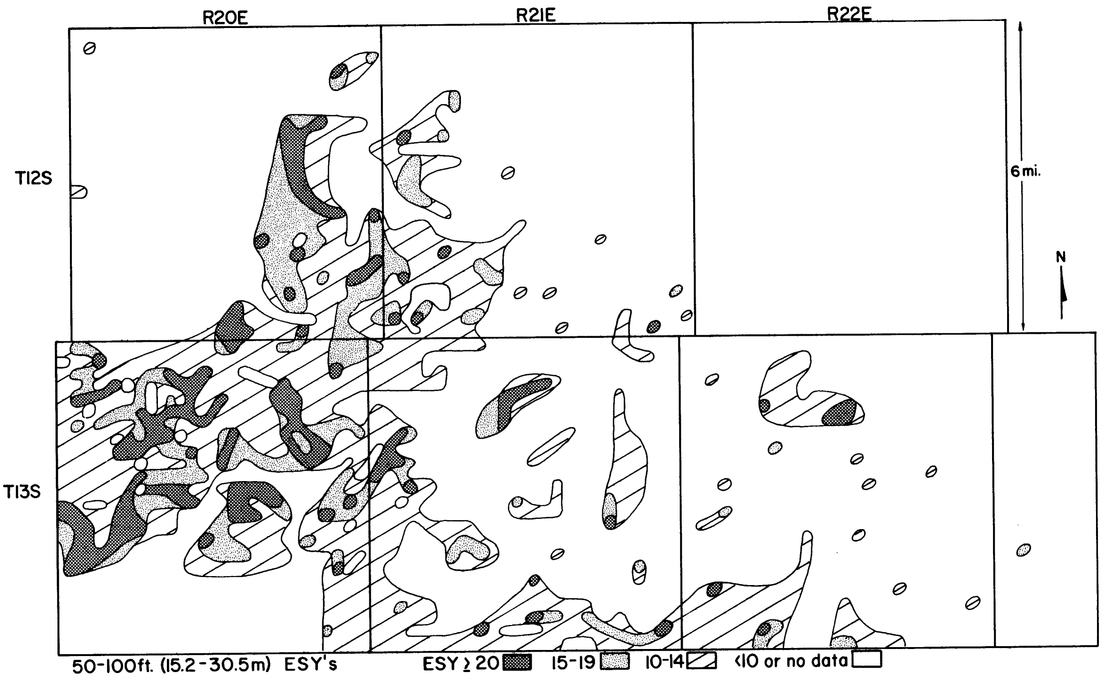


FIGURE 16.—Deeper estimated specific yield (ESY) diagram (50 to 100 ft, 15.2 to 30.5 m) important in injection well siting and in evaluating deeper aquifer continuities. The coarser sediments along the southern boarder are derived from the smaller streams—Fancher Creek and Redbank Slough.

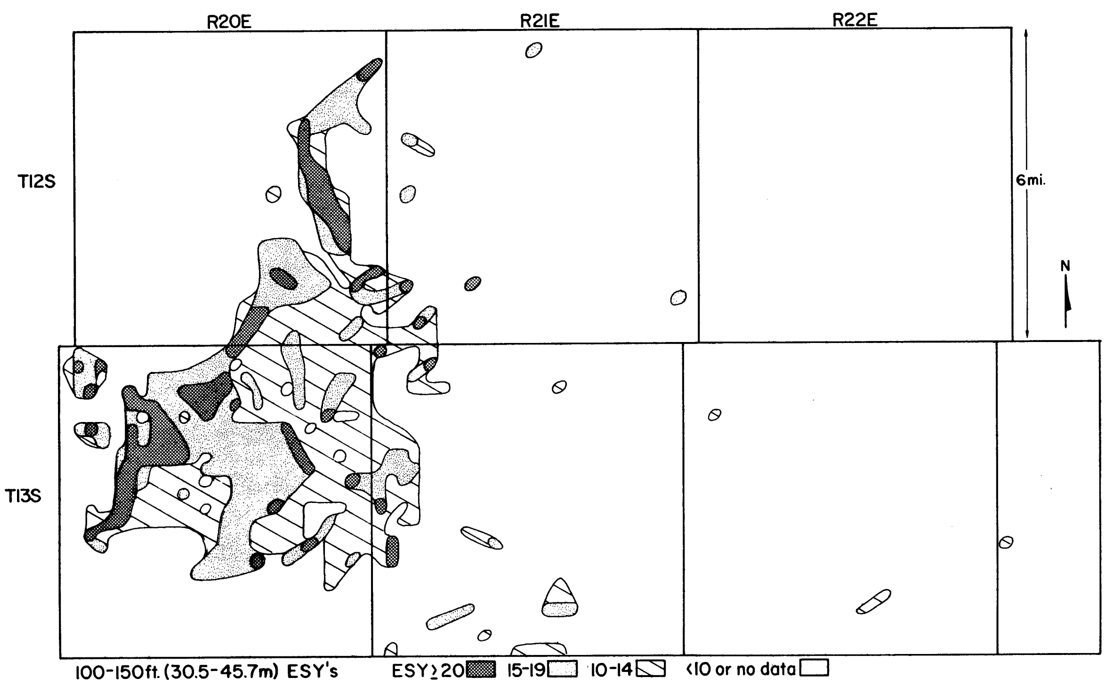


FIGURE 17.—Deeper estimated specific yield (ESY) diagram (100 to 150 ft, 30.5 to 45.7 m) important in injection well siting and in evaluating deeper aquifer continuities. Fewer wells penetrate to these depths in the eastern portion of the diagram; thus, the diagram shows an extensive amount of less than 10 or no data in this region.

- The basic hydraulics and aquifer properties of the area should be known, that is, what is the regional hydraulic gradient, and what are the major areas of stress (pumping) on this system?
- Based on the hydraulics of the area, the recharge wells should be located where they will most affect the ground water system (being upgradient or within the areas of stress).
- In picking areas in which to site injection wells, look for coarse stream channel derived or related sediments. If possible, locate sites that will have the maximum lateral continuities of coarser grained sediments (aquifers), thus dispersing and transporting the greatest amount of recharged water to the greatest possible area.
- When picking sites, consider the physical constraints of water access and the land necessary to construct and operate the facility.

Chapter 2.– Computer Analysis of Ground Water Regime from Well Driller's Logs

INTRODUCTION

In many areas of the country, it has become apparent that ground water extractions exceed recharge, causing a gradual lowering of ground water levels and a reduction of ground water storage. The ground water basin and its intrinsic storage capacity thus plays an important role in the domestic, industrial, and agricultural water supplies of an area; foresight is important in management of this valuable resource.

The identification of aquifer boundaries, both horizontal and vertical, is extremely difficult in most of California's alluvial-filled valleys. In the past, this identification has been done on a gross scale by the construction of geologic cross-sections, using driller's logs of water wells, and a few electric logs of oil and gas wells. This method identifies generalized formational and member boundaries but does not provide the physical parameters required to describe storage responses within ground water basins, particularly those in which older buried stream channels provide the medium where comparatively larger volumes of water are transmitted due to their greater specific yield and transmissivity values compared with deposits of finer grained material for a given area. Consequently, a new approach was developed by the DWR (*16*), which used digital computer methods to determine the continuity and extent of the various aquifers present in Alameda, Santa Clara, Sonoma, and Sacramento Counties. The technique uses information available to government agencies in the form of water well driller's logs, which, considering the cost of sample coring, are invaluable. A modified version of this technique was used to analyze the subsurface geology of the Fresno area.

The computer work was completed in two phases. Phase I identified the geology in terms of "material" to facilitate the location of physiographic features, such as stream channels and faults, which might affect the movement of water through the basin. Phase II took the computed numeric data and converted them into terms of storage capacities, transmissivity values, and other geohydrologic parameters, which are necessary for the development of a mathematical model for the Fresno ground water basin.

Two results were desired from the study utilizing DWR's computer techniques: (1) To establish the type of information that could be derived from data on hand, and (2) to organize the raw data and resultant interpretive material into a reference format for future use.

STUDY AREA

The area of this report comprises about 183 mi^2 (474 km^2) (117,120 acres or 47,399 ha) in the central part of Fresno County (fig. 18). It is bounded on the east by the foothills of the Sierra Nevada, on the west by Marks Avenue, on the south by Belmont Avenue, and on the north by the San Joaquin River. The northeastern section of Fresno and the city of Clovis are encompassed by the boundaries that were drawn with respect to the availability of driller's logs to the north and east and the estimated extent of the effect of ground water influent on the Fresno–Clovis metropolitan area to the west and south.

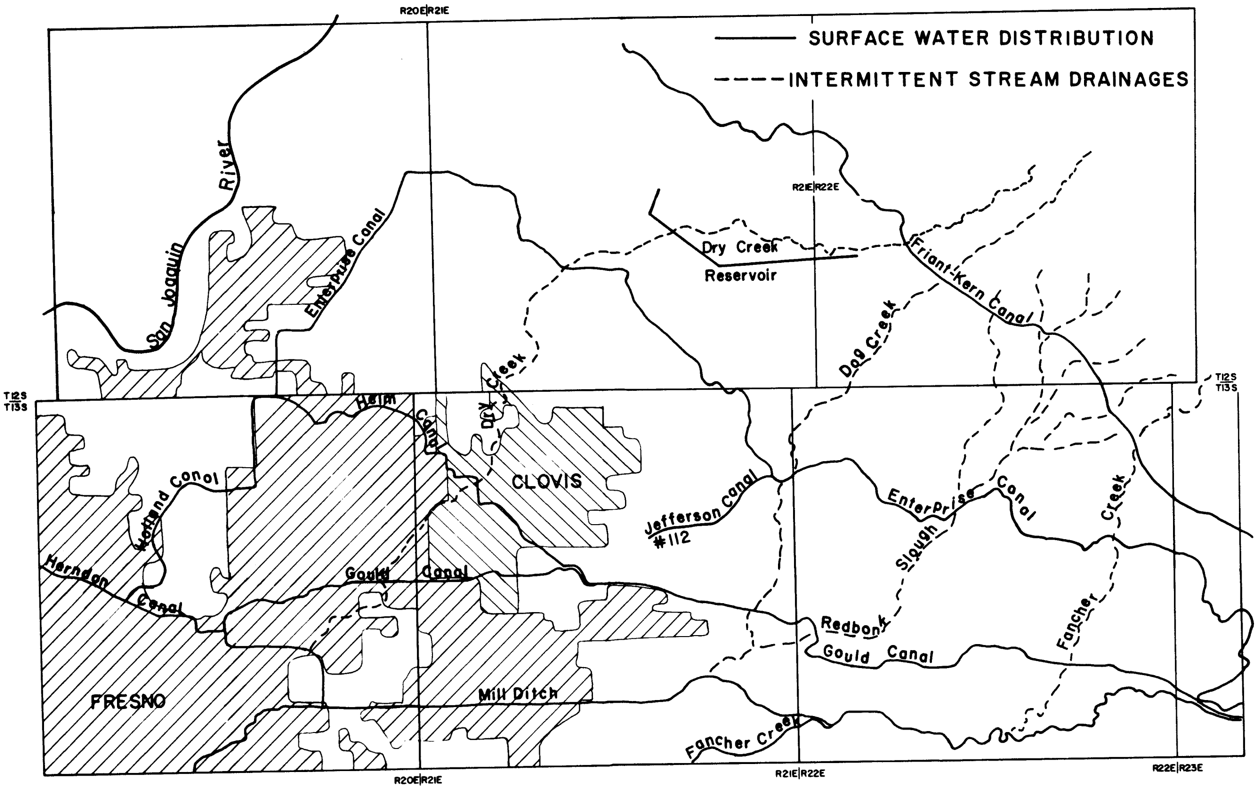


FIGURE 18.—Township nodal boundaries and influent water systems.

PROCEDURES

The first consideration of an investigation of this type is to divide the area of interest into as many workable units (nodes) as is deemed necessary. Initially, townships are chosen because the DWR GEOLOG program is written to print township plots (fig. 18). Further appraisal of the area using the GEOLOG printout could establish a new set of nodes of varying sizes and polygonal shapes that delineate areas of similar transmissivities, storage capacities, or varied geomorphologic characteristics to quantify any interaction. In the case of the Fresno study, township nodes were used (fig. 18) as they are a convenient working unit in terms of well numbering, workable output format, and easy interpretation without jeopardizing definition or clarity of the data. Earlier studies used quarter-township nodes, but they proved to be too cumbersome.

The following sequence for handling well log data is seen on the flow chart (fig. 19) used in this investigation. Listings were made using the compilations of driller's logs (fig. 20) submitted to the DWR and the County Department of Public Health. In 1951, section 13751 of the California Water Code required licensed water well drillers to file these logs with DWR, and, in 1974, County Ordinance No. 470-A-39 required the same log be submitted to the Public Health Department. The log identifies strata of varying alluvial material types and their interface depths. These strata are translated into percentage values known as ESY's. The specific yield of a soil or alluvial material by definition is the ratio of the volume of water which, after being saturated, is yielded by gravity to the volume of material in question. Values for the ESY are assigned to each of the materials reported on the logs as designated in the U.S. Geological Survey Water-Supply Paper 1469, "Ground Water Conditions and Storage Capacity in the San Joaquin Valley" (table 7). Additional research on the subject is found in U.S. Geological Survey Water-Supply Paper 1662-D, "Specific Yield—Compilation of Specific Yields for Various Materials," by A. I. Johnson. ESY is defined as being equal to the specific yield of a given material under unconfined conditions. The ESY of a material is a pure number and remains the same whether the material contains ground water under confined or

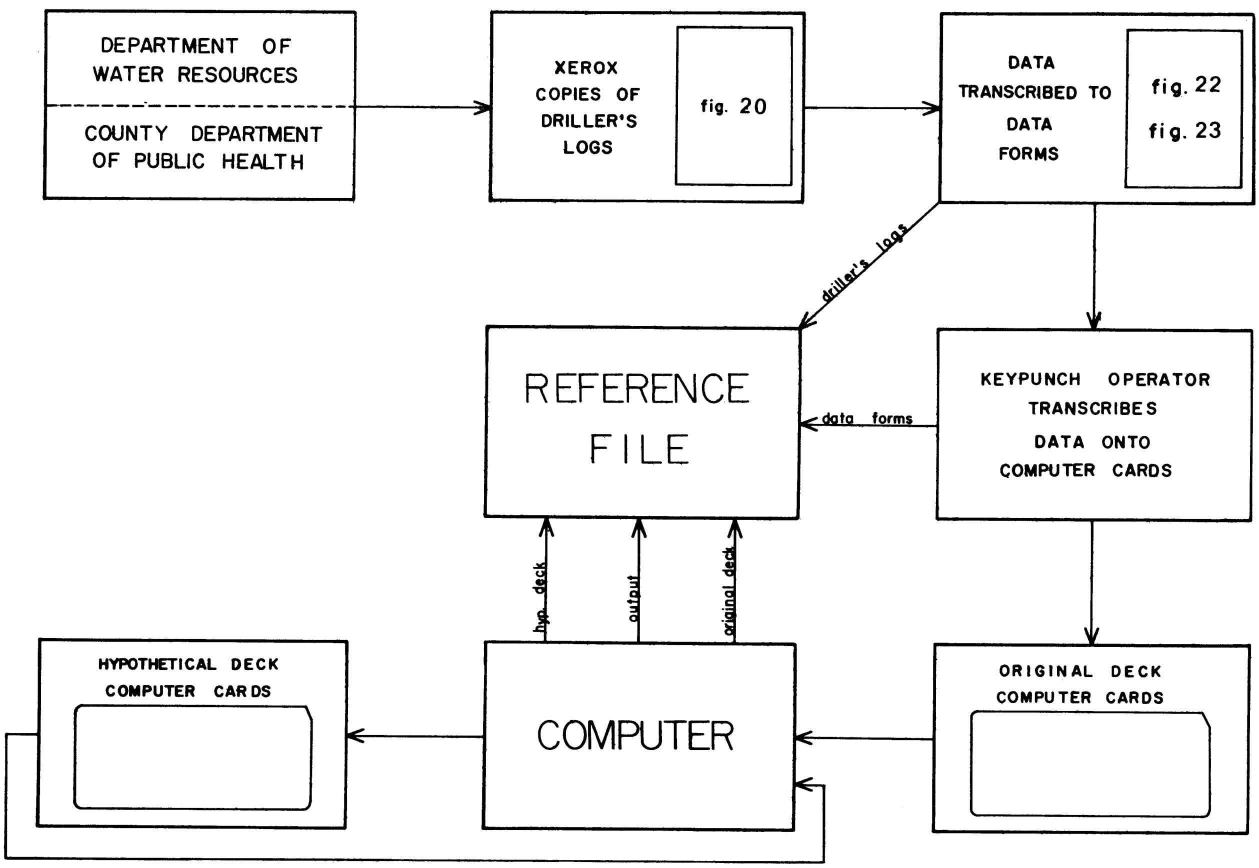


FIGURE 19.—Data processing flow chart. No data are retained in computer memory.

ORIGINAL
File Original, Duplicate and Triplicate with the
REGIONAL WATER POLLUTION
CONTROL BOARD No. 5
(Insert appropriate number)

WATER WELL DRILLERS REPORT
(Sections 7076, 7077, 7078, Water Code)

STATE OF CALIFORNIA

Do Not Fill In
No 41473
State Well No.
Other Well No.

(1) OWNER:
Name Fresno County Waterworks
Address 420 Equitable Building
Fresno, California

(2) LOCATION OF WELL:
County Fresno Owner's number, if any—
R. F. D. or Street No. Palm & Barstow Aves
Township 13 South
Range 20 East
Section 9

(3) TYPE OF WORK (check):
New well XX Deepening ☐ Reconditioning ☐ Abandon ☐
If abandonment, describe material and procedure in Item 11.

(4) PROPOSED USE (check):
Domestic ☐ Industrial ☐ Municipal XX
Irrigation ☐ Test Well ☐ Other ☐

(5) EQUIPMENT:
Rotary ☐
Cable XX
Dug Well ☐

(6) CASING INSTALLED:
SINGLE XX DOUBLE ☐

From ft. to ft. Diam. Gage or Wall | If gravel packed: Diameter of Bore, from ft. to ft.

143' of 16" 10 ga
20' of 16" 8 ga
Liner
64' of 14" 10 ga Liner begins @180'
20' of 14" 8 ga liner ends @264'

Type and size of shoe or well ring 16" & 14" Size of gravel:
Describe joint hard steel 10 ga

(7) PERFORATIONS:
Type of perforator used
Size of perforations in., length, by in.
From ft. to ft. Perf. per row Rows per ft.

(8) CONSTRUCTION:
Was a surface sanitary seal provided? ☐ Yes ☐ No To what depth ft.
Were any strata sealed against pollution? ☐ Yes ☐ No If yes, note depth of strata
From ft. to ft.
all welded casing
Method of Sealing

(9) WATER LEVELS:
Depth at which water was first found 80' ft.
Standing level before perforating ft.
Standing level after perforating ft.

(10) WELL TESTS:
Was a pump test made? XX Yes ☐ No If yes, by whom? F. M. Weldon
16" Yield: 3000 gal./min. with 47' ft. draw down after 47 hrs.
14" ~~Temperature of water~~ Liner 2000 33 Was a chemical analysis made? ☐ Yes ☐ No 33½
Was electric log made of well? ☐ Yes ☐ No

(11) WELL LOG:
Total depth ft. Depth of completed well 296' ft.
Formation: *Describe by color, character, size of material, and structure.*

From (ft.)	To (ft.)	Formation
0	2	topsoil
2	8	hardshale
8	10	sand
10	18	clay
18	23	sand
23	31	clay
31	52	sand
52	70	clay
70	111	sand
111	151	cobble stone
151	158	clay
158	164	hard shale (gray)
164	166	sand
166	178	clay
178	195	sand
195	197	clay
197	222	sand
222	223	pack sand
223	239	sand
239	245	clay
245	260	pack sand
260	263	sand
263	265	pack sand
265	269	hard shale
269	274	sand
274	305	alternating sand & clay

CONFIDENTIAL
Section 7076.1, Water Code

Work started Aug 10 19 . Completed Dec 2 1959

WELL DRILLER'S STATEMENT:
This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.

NAME Francis M. Weldon
(Person, firm, or corporation) (Typed or printed)
Address 2130 South Howard Ave.
Kerman, California
[SIGNED] Francis M. Weldon
Well Driller
License No. 110570 Dated Dec. 30, 1959

85689 2-54 30M QUIN SPO DWR FORM NO. 246 (REV. 3-54)

FIGURE 20.—Water well drillers report.

TABLE 7.—*Typical drillers' calls and their estimated specific yield (ESY) values*

Crystalline Bedrock ESY = 00 Percent			
Granite	Lava	Hard Rock	Rock
Clay and Shale ESY = 3 Percent			
Adobe	Dirt	Joint clay	Shell rock
Brittle	Granite clay	Muck	Silty clay loam
Boulders in clay	Hard clay	Mud	Sluch
Cemented clay	Hard pan	Poor clay	Smearey clay
Clay	Hard pan	Shale	Sticky clay
Clayey loam	Hard sandy shale	Shaley clay	Tight clay
Decomposed shale	Hard shale	Shell	Tule mud
Clayey Sand and Silt ESY = 5 Percent			
Cemented gravel	Gravelley clay	Rotten granite	Shaley gravel
Chalk rock	Hard packed sand	Sand and clay	Silt
Clay and gravel	Lava clay	Sand and silt	Silty clay
Clay with water	Loam	Sand clay loam	Silty loam
Clayey sand	Packed sand and shale	Sand rock	Silty sand
Clayey silt	Peat	Sand shell	Soil
Cobbles in clay	Peat and sand	Sandstone	Soil and boulders
Conglomerate	Porphyry clay	Sandy clay	Surface top soil washboard
Decomposed granite	Pumice stone	Sandy silt	
Dry sand and dirt	Rotten cement	Sediment	
Fine sandy loam	Rotten conglomerate	Seepage clay	
Cemented or Tight Sand or Gravel ESY = 10 Percent			
Arcade sand	Clay and loose rock	Hard gravel	Set gravel
Black	Clay with sand	Gravel with streaks	Sloppy sand
Brittle clay and sand	Cloggy sand	Hard sand	Soft sandstone
Blue sand	Conglomerate and clay	Heavy rocks	Tight boulders
Caliche	Coarse packed sand	Loose sandy clay	Tight coarse gravel
Cemented boulders	Dead gravel	Lava sand	Tight sand
Cemented gravel	Dead sand	Muddy sand	
Cemented sand	Dirty pack sand	Packed gravel	
Cemented sand and gravel	Fine sand	Sand crust	
Gravel and Boulders ESY = 15 Percent			
Cobbles and gravel	Gravel and boulders	Large gravel	Tight fine gravel
Coarse gravel	Heaving gravel	Rocks	Tight medium gravel
Boulders	Heavy gravel	Sand and gravel, silty	Muddy sand
Fine Sand ESY = 15 Percent			
Fine sand	Quicksand	Sand, gravel, and boulders	

TABLE 7.—*Typical drillers' calls and their estimated specific yield (ESY) values—Continued.*

Sand and Gravel ESY = 20 Percent			
Dry gravel	Gravelley	Running sand	Water gravel
Free sand	Gravelley sand	Sand and gravel	Water sand
Loose gravel	Medium gravel	Sand	
Coarse Sand and Fine Gravel ESY = 25 Percent			
Coarse sand	Fine gravel	Medium sand	Sand and pea gravel

Source: U.S. Geological Survey Water-Supply Paper 1469.

unconfined conditions or is completely dewatered as it relates to the relative sediment size and related porosity.

In our application of ESY percentages to driller's descriptions, we altered DWR's original intent, which was to identify the highest yielding aquifer sediments to more nearly coincide with depositional grain sizes (smaller ESY's correlating to finer sediment) yet still give some indication of yield. When inspecting Fresno area well logs, we noticed that the greatest portion of the descriptive terms were "sand" and "clay." This type of simplicity in the well logs tends to delete much of the discriminating resolution originally hoped for in the area. Instead, we tried to discern what we could from the less than scientifically complete, but free, information available on the logs. Thus, the descriptive terms were regrouped as shown in the following list of driller's calls and the ESY values used in this report:

ESY = 3 Percent

Clays, all colors, hardnesses, and types
Hard pan
Hard shale

ESY = 5 Percent

Top soil
Sandy clays
Decomposed granite

ESY = 10 Percent

Sandy top soil
Clayey sand
Fine sand
Packed sand
Layers of sand and clay
Clay and rock

ESY = 25 Percent

Sand, all colors and types, without grain size modifier
Medium sand, all colors
Coarse sand, all colors
Sand and gravel
Cobbles

This regrouping also circumvents a fallacy in the DWR application of ESY to driller's terms. As an example, DWR lists cemented gravel, a "coarse" stream channel deposit, under the 5-percent ESY heading. This individual ESY is probably correct, but their intent of delineating old channels by this ESY grouping (table 7) is not entirely possible as they are identifying only the most yielding or transmissive sediments, which may not necessarily equate to old buried stream channel sediments, of which gravels are definitely a part. In the Fresno area, some of these types of problems never arose, but we felt our purposes would be better served with the type of grouping found in the above listing.

Each well must be located on a map and assigned a location identity code, which includes township, range, section, and quarter-quarter section designation (fig. 21). The "ICOL" and "LINE" numbers are derived from the GEOLOG township matrix (fig. 21) that the computer uses to locate the log in plotting. The identity number along with the log data, well head elevation, and number of layers are entered on the well log data from figure 22, whereas all other pertinent well data, including a driller's code number, are entered on well log data form 2 (fig. 23). These are then transcribed by a keypunch operator onto computer cards.

In quarter-quarter sections containing more than one well log, DWR uses the deepest well log to represent the whole quarter-quarter section. The Fresno study area is relatively small and deals primarily with smaller complex intermittent stream drainages. Therefore, an additional program was written, which averages the ESY values for 5-ft (1.5 m) increments starting from a reference elevation rounded to the nearest 10-ft (3 m) interval and combines these data with other averaged logs within the quarter-quarter section to give an overall average ESY for each interval. This is believed to be more representative while still providing maximum as well as minimum elevation ESY values. The end product was a computer punched deck of hypothetical wells (fig. 19), which were subsequently run through the computer, yielding the ESY output format.

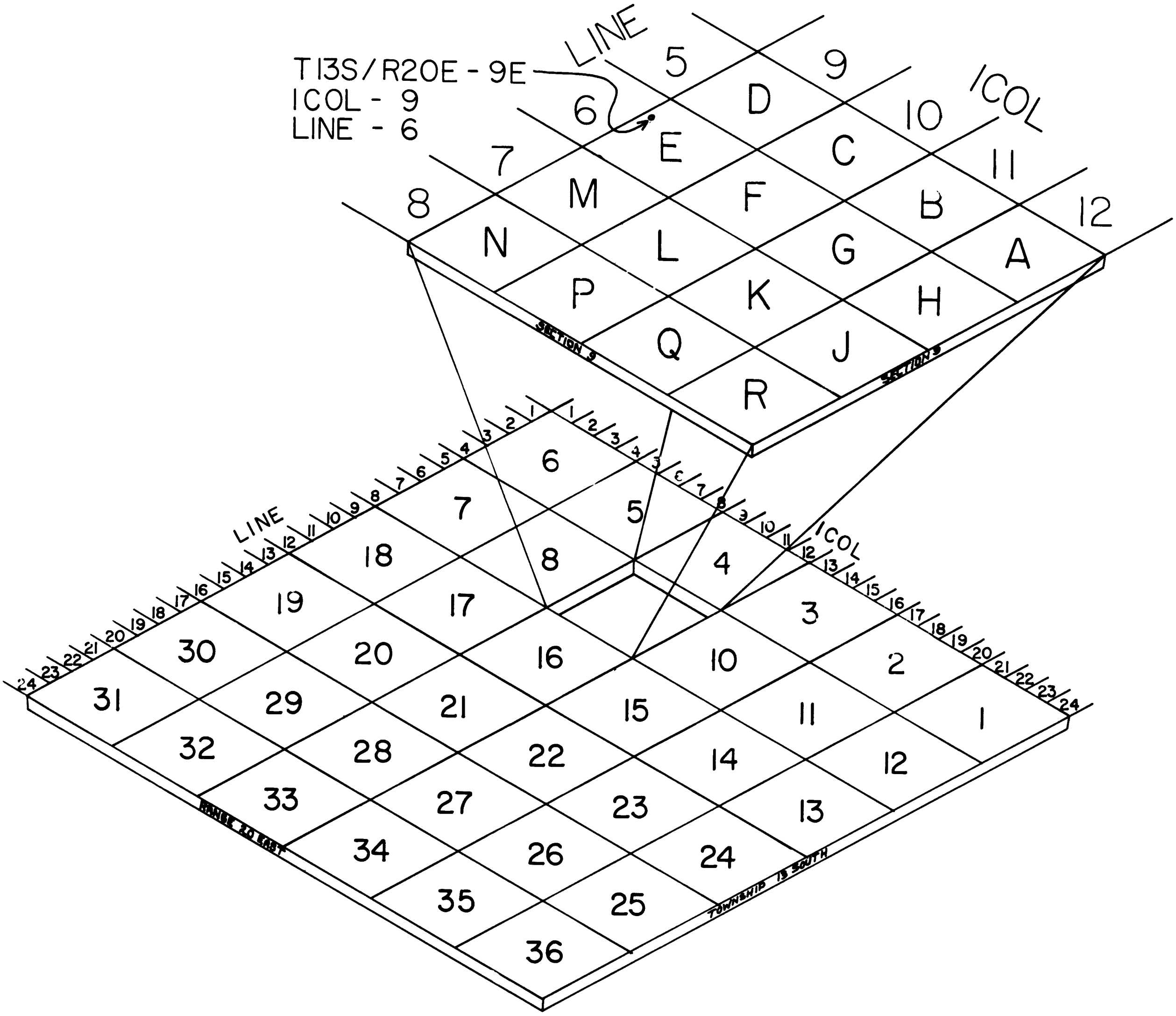


FIGURE 21.—Well identification number and geolog matrix diagram.

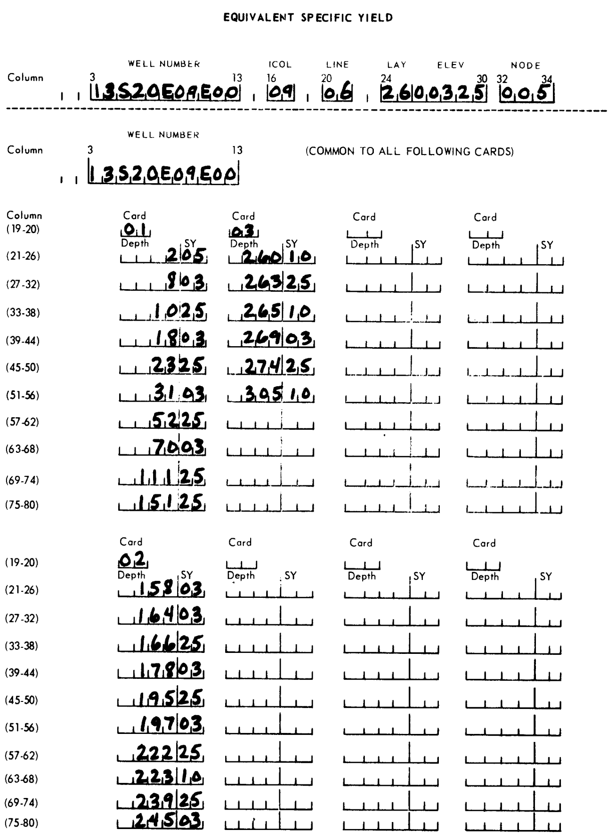


FIGURE 22.—Well log data form 1.

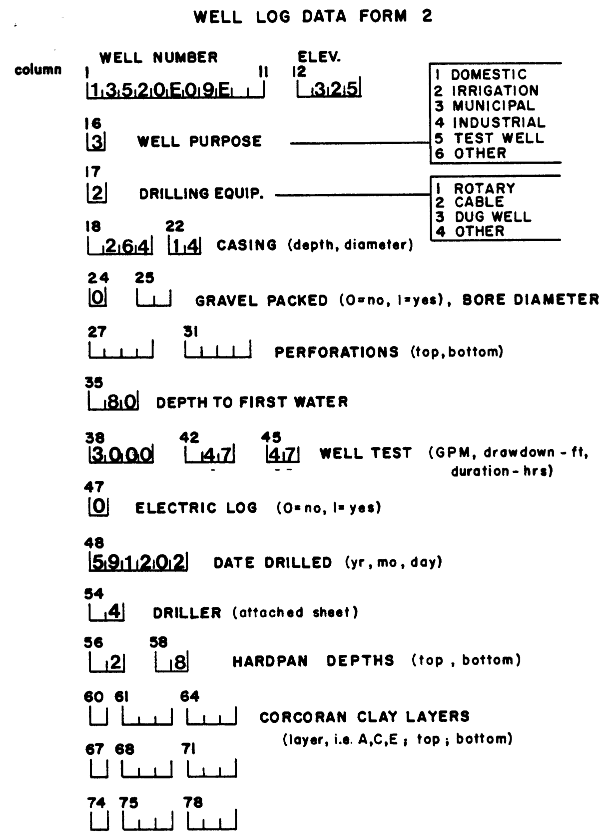


FIGURE 23.—Well log data form 2.

PROGRAM RESULTS

Subsurface Geology

Inherent in the deposition of coalescing alluvial fans, specifically those on the eastern side of the San Joaquin Valley, is the continuously changing lateral position of the stream channels and loci of deposition resulting in a highly variable depositional regime with time and subsurface depth. During the periods of normal runoff, the established stream course contains the coarsest grained materials, ranging from large gravels, cobbles, and boulders near the foothills to sand and silt near the axis of the valley. Adjacent to the stream channel are finer sands, silts, and clays, which grade outward to even finer grained flood plain clays.

Channel directions shift during a single flood or successive floods and result largely from the progressive filling of the channels, often as a result of blockage by boulders and mudflows or by crevasse splays from channel ridge deposits due to overbank flooding or bank failure. These channel changes ensure maintenance of the fan form by distributing material widely over the surface. With time and continued deposition, the abandoned stream channel is covered with younger, finer grained levee and flood plain alluvium, isolating the old stream channel and converting it into a lenticular aquifer. In some cases, new stream channel positions form alongside or cross older channels, thus creating horizontal and vertical areas of hydraulic continuity between superimposed channel deposits of different ages. The juxtaposition of channels of differing bedloads and gradients gives rise to channel piracy and displacement. Prior to their incision, the perennial San Joaquin and Kings Rivers deposits, in effect, controlled the depositional patterns of the intermittent streams (Dry Creek, Dog Creek, Fancher Creek, and Redbank Slough) by their greater volumes and velocities with coincident increases in bedload and suspended load, which gave rise to more extensive sedimentary deposits.

ESY and Hardpan Delineation Diagrams

ESY and hardpan delineation diagrams were constructed to define the subsurface geology with regard to paleochannel migrations and the potential for accessing these more permeable and transmissive sediments to recharged water. Four programs written for the hypothetical well logs accomplished the following: (1) Averaged the entire depth (generally to 61 m) of each log (fig. 12); (2) averaged the top 20 ft (6.1 m) of each log (fig. 8); (3) averaged the logs in 50-ft (15.2 m) increments down to 200 ft (61) (figs. 9, 16, 17, and 24); and (4) delineated the presence and the depth to the top and bottom of the hardpan, this was done with two separate printouts. Figure 4 is a compilation of the two hardpan printouts and shows the hardpan distribution surface and subsurface.

The printout format was by townships with one two-digit ESY number for each quarter-quarter section (144 per township). The township printouts were then taped together and hand contoured. On the deeper diagrams (figs. 17 and 24), a certain amount of interpolation was employed because of the sparse array of data points. Each of the ESY diagrams delineated the occurrence of channel associated material (ESY greater than or equal to 10) and the general channel patterns of that increment.

The ESY diagrams just described were used instead of the data printout and synthesis employed by DWR in their GEOLOG program because of the ease, simplicity, and speed in delineation, whereas accuracy was not sacrificed.

These ESY and hardpan delineation diagrams thus form the data base upon which initial searches and probes are conducted (either by drilling or geophysical methods) for recharge

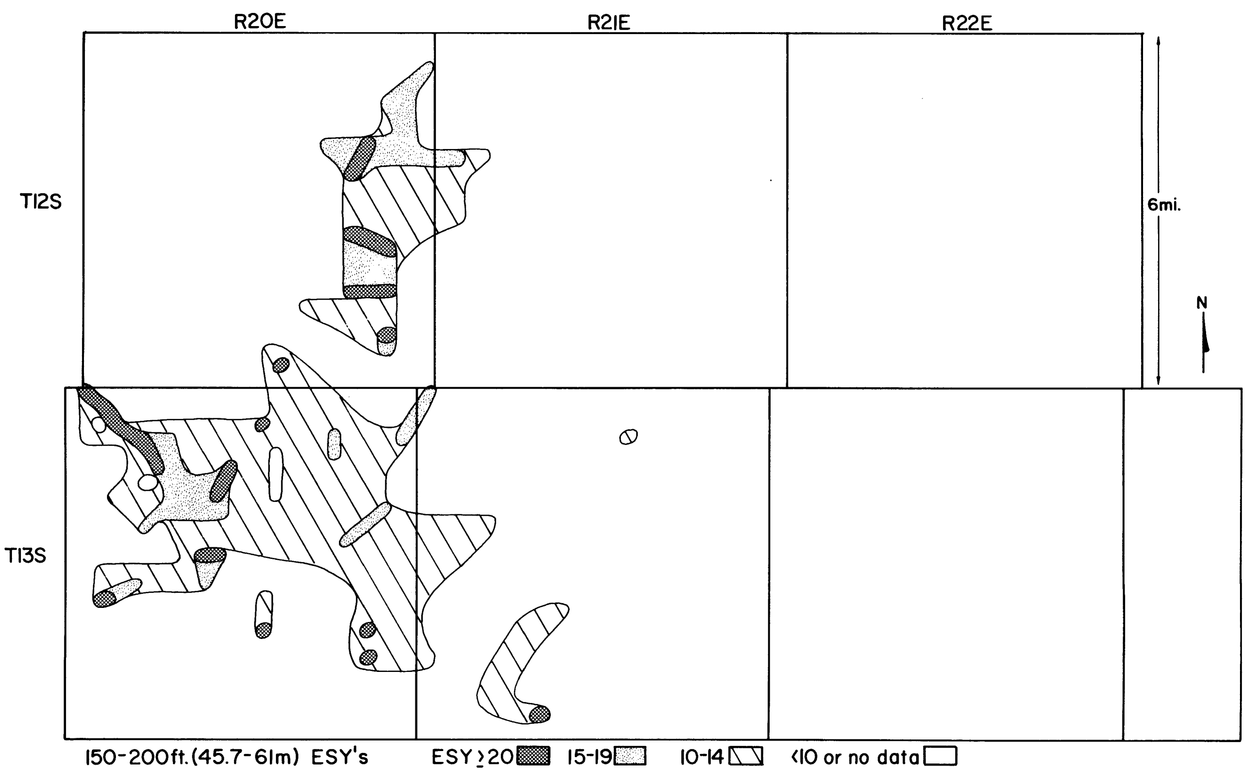


FIGURE 24.—Diagram of 150- to 200-ft (45.7 to 61 m) averaged incremental estimated specific yield. Only the deeper City of Fresno wells penetrate to this depth, and most are intercepting San Joaquin River sediments.

sites that have the most permeable surface sediments (higher ESY's) and the most continuous transmissive subsurface aquifers.

GEOLOG Program Interpretation

The DWR GEOLOG program, ultimately, was not used because of the complicated process of transferring computer material to a visual medium and the complex and prolonged interpretation necessary to define channel material from the visual medium. Also, within the Fresno area, the complex sequence of alluvial sediments deposited by major rivers and intermittent streams proved too complicated for interpretation of the data generated by the GEOLOG program, even though some possibilities for excellent data interpretation exist.

A brief explanation of the GEOLOG program and its results for Fresno follows. The GEOLOG program converts the averaged ESY values to the following symbolic form for utilization in graphic representation:

Symbol	*Range of ESY values*	*Typical materials*
*	0	Hard rock.
.	1 to 7	Clay and silt.
–	8 to 12	Clay and fine sand.
+	13 to 17	Sand with clay streaks.
0	18 to 25	Gravel and coarse sand.

This representation is employed in the production of maps with each printout denoting a township. Each printout represents a 10-ft (3 m) thickness of the ground water basin and is identified by its appropriate subsurface elevation above mean sea level. The township printouts are assembled in mosaic fashion and transferred to a transparent media that, arranged by elevation, represents a three-dimensional view of the ground water basin.

Five 10-ft (3 m) horizontal sections (mosaic transparencies, encompassing study area limits) were stacked to establish the channel lineation continuity and lateral extent with regard to depth. The characteristics of depositional environments will be peculiar to any area, requiring a decision to define major drainages in terms of symbolic ESY values of 25 percent or all layers represented having "0" symbols. Because of shallow well depths, there were places where less than five layers were available for the 50 ft (15.2 m), but they were included within the boundaries if they possessed the maximum ESY values.

Because of the natural slope of the channel deposits, each channel will pass through the horizontal levels or planes and ideally appear as an elongated oval. When a sequence of levels is viewed from above, a stream channel can be seen meandering downward through the various levels. In viewing the levels, channel deposits may appear to end abruptly. Some of these discontinuities could be attributed to erosional features. If, however, a number of discontinuities appear to fall in a line, this may denote a fault trace. This situation was substantiated in the Sacramento County study by correlation with previously mapped fault zones.

A primary objective of the DWR programs and this study is the location of zones with good water-bearing aquifer material. The GEOLOG printouts provided the means to construct the diagram seen in figure 25. The diagram, besides showing these features, shows the most recent migration of the intermittent stream drainages. The present channels appear to have migrated south from the predominant channel migrations denoted by the diagram. This is historically representative for the deposition of material to the depth of available data. Channel migration seemingly is related to the incision of the San Joaquin and Kings River drainages, that is, an easing of the external pressures on the interfan area, an accumulation of material in the center, and a lateral migration towards the limbs of the fan.

Numeric Data Interpretation

Before making any interpretation of the numeric data produced by the GEOLOG program, it was necessary to decide at what point the data become valid. For our purpose, it was decided that the general well log representation (fig. 26) becomes valid when at least seven wells, or 5 percent of the total possible representation, is present in a quarter-township for any given elevation. The Fresno study area encompasses 117,120 acres (47,398 ha) or 2,928 quarter-

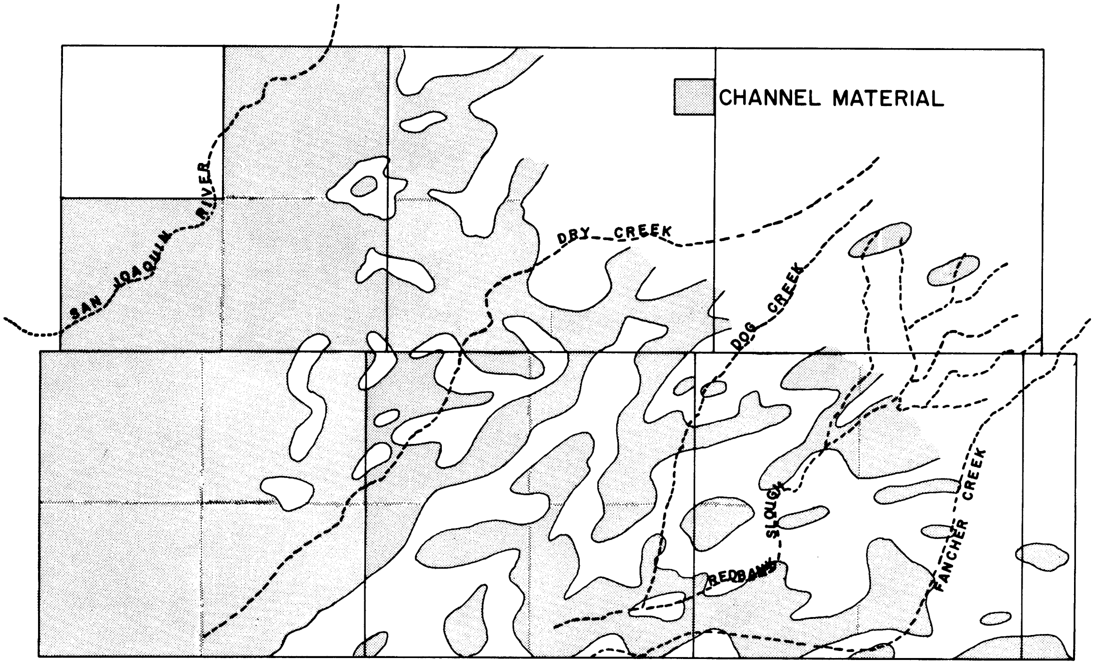


FIGURE 25.—Maximum extent of channel migration.

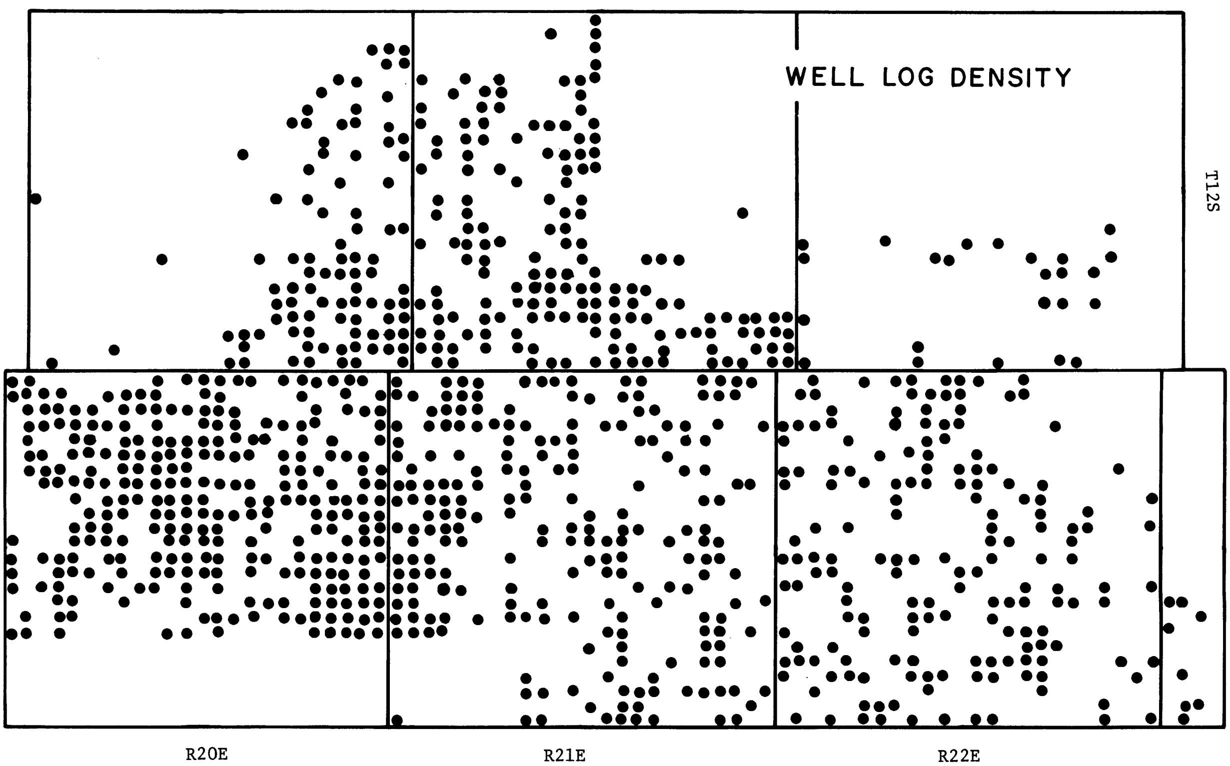


FIGURE 26.—Node well log density diagram.

quarter sections. Thirty-two percent of the quarter-quarter sections were represented by at least one well log. In the years since the compilation of the well logs used in this study, as many as 300 wells may have been drilled in the northeast area as a result of rural development, and the estimated representation now approaches 50 percent. This additional information would be valuable in filling the data gaps apparent in the present study.

At the upper elevations of a node and in nodes with a few deep wells, the upper and lower elevations produce data that are weighted rather than representative. For example, a node of average representation has one or two deep wells, which in the lower stratum penetrates an old stream channel, and indicates such by showing up as gravels and coarse sands on the driller's logs. This information distorts calculated storage capacity values since an ESY of 25 percent is assumed for the whole area, when, in fact, the highest average ESY for any nodal layer in the area is 20 percent, which would mean a difference for any 10-ft (3 m) interval of at least 2,880 acre-ft (3.55×10^6 m^3) or nearly a billion gallons of water.

The overall storage capacity of the ground water basin may be interpolated for the unlogged material from the calculated values. The upper 200 ft (61 m) (average well depth) will be similar to the underlying material since the stream drainages are simply migrating back and forth between the basin limits (San Joaquin and Kings Rivers). The calculated total storage capacity for the upper 200 ft (61 m) of alluvium bounded by the nodal limits is approximately 2.36 million acre-ft (2.91×10^9 m^3). The data for individual one-quarter township nodes are found in table 8.

RECOMMENDATIONS

Several suggestions can be made for a more complete use of the well log data. Computer analysis involves the evolution of raw data into workable information formats. The computer is programed to take bits of information and perform certain functions with it. Nonrelated information is then disregarded; however, the functions of the computer are limited by the quality and quantity of input data. At the outset of the investigation, all seemingly unrelated information should be entered on the computer cards for future use no matter what the study at the time dictates. This procedure involves little additional time and would provide a beneficial reference resource tool. For example, the following might be considered as additional entries: (1) Color coding of the clays or other units in the profile (thus describing their oxidizing and reducing environments (similar program developed by DWR)), (2) the horsepower and bowl setting of the completed wells, or (3) the base of the fresh ground water (2,000 parts per million or 2,000 micromhos). This additional information can easily be included as another data card behind the existing formats (figs. 22 and 23).

When all of the well data have been stored in the computer, some useful and interesting information and statistics may be developed. For example, plotting either histograms or graphs of wells drilled versus time might indicate how average annual rainfall or average annual runoff from a nearby mountain range is responsible for well drilling needed to offset the lack of surface water. Has the type of wells drilled changed through time (that is, are rotary wells becoming more common)? Based on initial well tests, are particular areas more productive than others? The depth to water is useful in indicating water level trends of an area through time, especially in an area that has seen little previous pumping. In Fresno County, both the near-surface hardpan and the deeper Corcoran Clay are important units and thus were included on well form 2; the hardpan is significant for its low permeabilities, which might preclude ponded recharge in specific locales, whereas the Corcoran Clay separates the San Joaquin Valley alluvial fill into an upper and lower group of aquifers with differing water qualities. Thus the occurrence, thickness, and depth of these units is of interest.

Through the use of these techniques, it will become possible to undertake detailed analyses of ground water systems at almost any level required, the only constraint being the number of adequate well logs at the depth of interest.

TABLE 8.—*Nodal averages and estimates of the northeast Fresno-Clovis hydrologic study*

Nodes (1/4 townships)	Number of hypothetical wells	Well representation (percent)	Control elevation (feet)[1]	Maximum depth (feet)	Usable depth for data computations (feet)	Average estimated specific yield (ESY)[2] (percent)	Storage capacity for upper 200 ft ($\times 10^4$ acre-feet)
NE¼, T. 12 S., R. 20 E.	27	19	360	300	240	13.27	15.28
NW¼, T. 12 S., R. 21 E.	46	32	400	400	310	7.31	8.42
SW¼, T. 12 S., R. 20 E.	5	3	260	100	—	[3]13.58	15.6
SE¼, T. 12 S., R. 20 E.	61	42	360	350	220	15.48	17.84
SW¼, T. 12 S., R. 21 E.	71	49	370	340	210	8.54	9.84
SE¼, T. 12 S., R. 21 E.	45	31	400	250	180	8.88	10.23
SW¼, T. 12 S., R. 22 E.	10	7	450	150	110	4.37	5.00
SE¼, T. 12 S., R. 22 E.	14	10	500	190	100	5.16	5.94
NW¼, T. 13 S., R. 20 E.	95	66	320	350	300	15.42	17.77
NE¼, T. 13 S., R. 20 E.	96	67	330	390	300	14.31	16.49
NW¼, T. 13 S., R. 21 E.	77	53	350	310	250	9.4	10.83
NE¼, T. 13 S., R. 21 E.	46	32	380	180	160	9.42	10.85
NW¼, T. 13 S., R. 22 E.	49	34	400	310	160	6.72	7.74
NE¼, T. 13 S., R. 22 E.	27	19	430	180	140	7.48	8.62
SW¼, T. 13 S., R. 20 E.	36	25	300	520	280	14.21	16.37
SE¼, T. 13 S., R. 20 E.	50	35	310	310	280	12.43	14.32
SW¼, T. 13 S., R. 21 E.	34	24	330	320	220	9.74	11.22
SE¼, T. 13 S., R. 21 E.	54	38	350	230	170	9.41	10.84
SW¼, T. 13 S., R. 22 E.	53	37	370	180	170	7.74	8.92
SE¼, T. 13 S., R. 22 E.	46	32	400	210	160	8.99	10.36

[1] Average mean sea level; elevation at center of node.

[2] Computed from usable depth data.

[3] Average ESY from data available.

Chapter 3.–Alluvial Geology and Related Hydrology of the Urban Fresno Area

INTRODUCTION

The Fresno–Clovis metropolitan area is dependent solely upon ground water for its municipal, industrial, and agricultural processing needs. The surrounding agricultural communities utilize ground water for virtually all of their domestic needs and for 40 to 50 percent of their agricultural irrigation water requirements. Statewide agricultural irrigation accounts for 85 percent of all water used in California. The Fresno metropolitan–agricultural area (fig. 27) straddles the high alluvial fans of the perennial San Joaquin and Kings Rivers and the medial compound alluvial fan of intermittent streams (*55*). The deposits form the principal ground water reservoir in many areas, and the recharge of many ground water basins is through the alluvial fans that fringe the basin. The surfaces of many fans are highly desirable for agricultural, urban, and industrial uses (*14*). This is the case in the Fresno metropolitan-agricultural area.

The intent of this study is to define the sedimentary origins, depositional processes and environments, lithologies and textures, areal extents of these features, and historical sequence of events involved in the formation of these alluvial fans. The principal application of this information will be in the description of fan hydrology; more specifically, the origin and movement of the ground water, and the existing and projected effects of pumping and artificial recharge on the flow dynamics of the aquifer system.

Previous Work

Most earlier studies have been hydrologic or geohydrologic in nature (*18*, *20*, *21*, *40*, *49*, *55*, *59*). Huntington (*37*) classified the soils in the Fresno area, whereas McDonald (*42*), Bateman and Wahrhaftig (*7*), and Janda (*39*) dealt with the alluvial and adjacent Sierra Nevada geology.

General Geology

The Fresno area alluvial fans (fig. 28) form part of a continuum of fans along the eastern margin of the San Joaquin Valley structural trough. These sediments are derived from the Sierra Nevada to the east. The southern Sierra Nevada is formed by a tilted fault block composed of a sequence of Mesozoic granitic plutons of different compositions, with belts of Paleozoic and Mesozoic metamorphic pendants and ultrabasic rocks along the western margin and crest of the range. Smaller volumes of tertiary volcanic material are found in the San Joaquin and Kings drainages east of Fresno.

The present Fresno alluvial fans are the most recent of a sequence of Cenozoic sedimentary

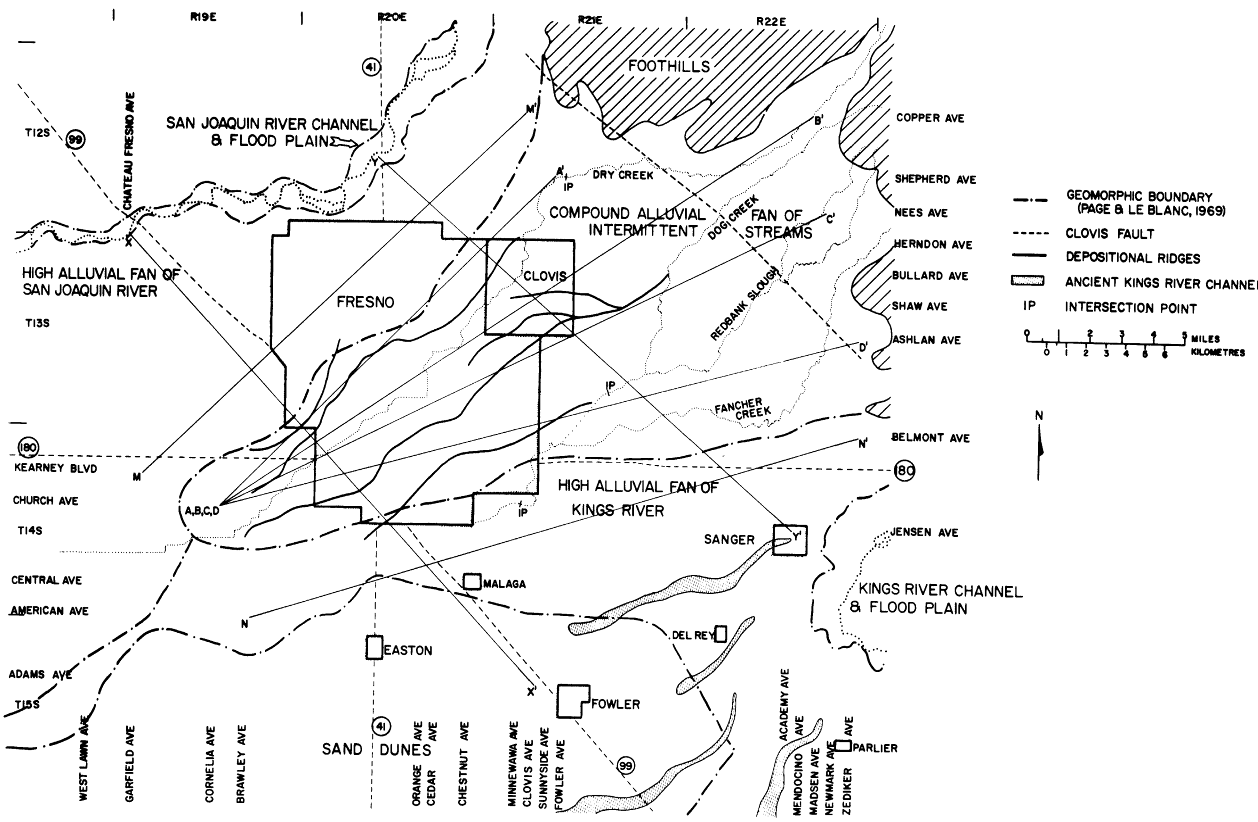


FIGURE 27.—The Fresno metropolitan-agricultural area showing the geomorphic subdivisions (*55*), the major water courses, and some depositional and erosional features of the fans. The locations of cross sections *A*, *B*, *C*, *D*, *M*, *N*, *X*, and *Y* (shown in fig. 30) are displayed.

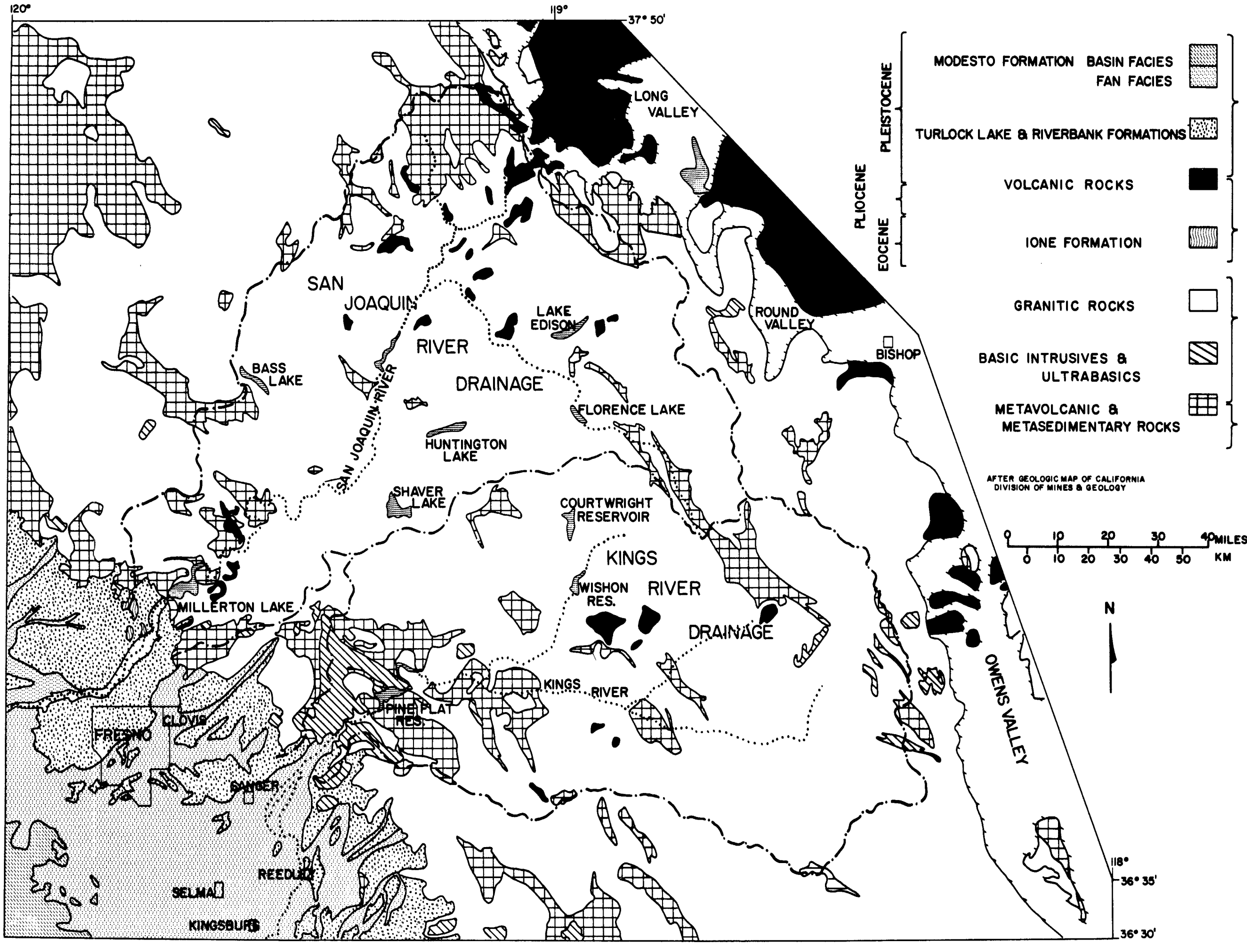


FIGURE 28.—Geologic setting of Fresno with respect to Sierra Nevada rock types in the San Joaquin and Kings River drainages and the Quaternary alluvial deposits of the San Joaquin Valley.

deposits that in the axis of the San Joaquin Valley exceeds 30,000 ft (9140 m) (*32*). The Jurassic through Oligocene deposits are principally marine with the Miocene-Pliocene deposits ranging from continental in the north to marine in the south, whereas the Pleistocene and Recent deposits are of lacustrine and fluvial origin. The marine sediments contribute saline connate water to the San Joaquin Valley's upper, previously fresh water aquifers. Thus, water quality in the San Joaquin Valley degrades with depth as the diffusion boundary of this water of higher salinity and density is approached (fig. 29). These valley fill sediments and the present Sierra Nevada landscape provide a record of tectonism and erosion as the Sierra Nevada was unroofed during the late Cretaceous to Paleocene and again during renewed uplift in the late Miocene–early Pliocene. The Pliocene activity was responsible for the present height of the Sierra Nevada and the depth of incision of the major rivers (*7*). The most recent sediments of the eastern San Joaquin Valley, including the Fresno fans, owe part of their origin and depositional history to the Pleistocene glaciations and associated climatic conditions.

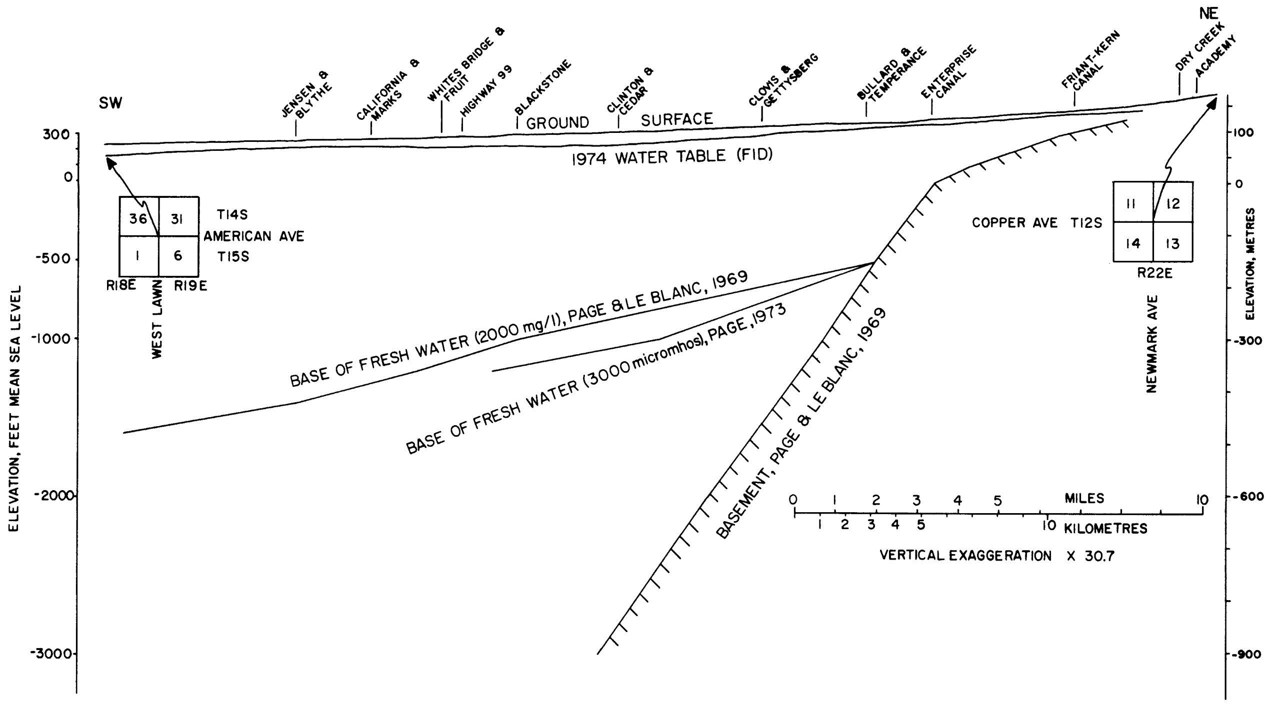


FIGURE 29.—Depth to the base of fresh water (*53*, *55*) and basement beneath Fresno. 1974 water table from Fresno Irrigation District data.

GEOLOGY OF THE FRESNO FANS

The alluvial fans of the eastern San Joaquin Valley do not match the typical physical characteristics and depositional parameters of the classic semiarid or desert alluvial fans (*11*, *14*). These east side fans have low relief with very gently gradients. Matthes (*46*) stated, "So gentle is this slope (of the fan) that to the travelers' eye the surface appears utterly flat." Blissenbach (*10*) indicated that "fans formed in humid environments commonly are flatter than those of arid environments owing to the abundance of running water which forms the development of gentler gradients." Even though the Fresno fans are in a low precipitation environment, the Sierra Nevada watersheds produced a large annual runoff at the time of their deposition.

The San Joaquin and Kings Rivers drain an 80-mi (129 km) lineal segment of the southern Sierra Nevada and have respective watersheds of 1,750 and 1,720 mi^2 (4,532 and 4,455 km^2), which extend from the crest at over 13,000 ft (3,962 m) to the Valley floor between 300 and 400 ft (91 and 122 m) (fig. 28) and receive an average of 45 inches (114 cm) of precipitation a year above 6,000 ft (1,829 m) (*15*). The San Joaquin River is the major drainage way north to San Francisco Bay, whereas the Kings River flows south into the landlocked Tulare Lake Basin and is separated by a low topographic divide originating from the San Joaquin River. A small range front watershed of 125 mi^2 (324 km^2), located between the San Joaquin and Kings Rivers, feeds four ephemeral streams, which course the medial compound alluvial fan. This small drainage receives a little more precipitation than the 10.5 inches (26.7 cm) average at Fresno (U.S. Weather Bureau reference data) some 18 to 25 mi (29 to 40 km) west.

The high alluvial fans of the San Joaquin and Kings Rivers (*55*) extend from the western edge of the Sierra to the axis of the San Joaquin Valley some 40 mi (64 km) distant, whereas the medial compound alluvial fan is 26 mi (42 km) long. The portions of the fans in the study area are between 650 and 250 ft (198 and 76 m) in elevation and have an average surface slope of less than 0° 10′ arc (15.4 ft/mi, 2.9 m/km).

The eastern San Joaquin Valley coalescing alluvial fans are individually formed by fluvial depositional processes of either a single major river or several smaller streams with the resulting deposits forming segments of a cone that have a concave radial profile and a convex cross fan profile (fig. 30) and contain little fossile material, similar to semiarid fans. Yet the east side fans are formed by meandering (and in some instances braided) stream-flood plain processes that contain more well-sorted, fine-grained material and have gentler slopes and a longer radial profile with greater areal surface than the semiarid fans on the west side of the San Joaquin Valley (*12*, *13*). The east side fans show a greater similarity in physical features, processes, and deposits to the large inland delta (alluvial fan) of the Kosi River, India (*31*), flowing from the Himalaya. In both the Kosi and eastern San Joaquin Valley locations, the watersheds and their downstream alluvial deposits are in different climatic realms—humid, higher precipitation mountainous areas adjacent to semiarid low precipitation plains. Because of this climatic difference, the eastern San Joaquin Valley fans show little similarity to the humid climate fans of the high Himalaya (*24*) or of the Canadian Rockies (*41*, *64*).

Alluvial Sedimentation of the Fresno Coalescing Fans

The alluvial processes and resultant deposits that form the Fresno fans are normally associated with an alluvial flood plain regime. The climatic setting, source rocks and their weathering characteristics, erosional transport distances, and the tectonic setting of the Great Valley with respect to the Sierra Nevada are all interrelated factors responsible for the different depositional and morphological character of these east side fans compared to the classic desert fans. Specifically, no sieve (*35*), sheetfloor, or debris and mudflow deposits (*14*) are found.

The Fresno fans consist of alluvial deposits formed by shifting rivers and streams having a wide range in flow durations and discharges (fig. 31). Currently, neither the San Joaquin nor the Kings Rivers are contributing to their own or adjoining high alluvial fans (*55*) because of channel incision approximately 200,000 years ago (*39*); however, their paleochannels have left a depositional record of lateral shifts back and forth across the fan, aggrading its surface. Within this former regime of migrating rivers and streams, the fan boundary interdigitations formed a complex coalescing alluvial fan system with potential for great vertical and lateral variability. Yet within this system, certain hydraulic and sedimentary parameters hold true; coarser material is found in proximal fan locations associated with stream channels while finer material is encountered down fan or adjacent to a channel as flood deposits. Depending upon flow regimes, certain physical features are formed on and in the alluvial deposits; some have been preserved in the sedimentary record as crossbedding (fig. 32), ripples, bar sequences, and erosion and deposition surfaces. Postdepositional features, due to loading and dewatering of the saturated sediments, occur as soft sediment deformation of bedding and laminae, injection features, and small dewatering volcanoes. All these preserved features offer a means of reconstructing the hydrodynamic and physical processes operating at that time.

Two major categories of alluvial deposits are found in the Fresno fans—vertical and lateral accretion deposits (*1*, *2*). Vertical accretion deposits include levee, proximal overbank, crevasse splay, and flood plain deposits. Lateral accretion deposits are channel lag, point bar, and, occasionally, channel bar deposits. All these deposit types are observed on the present fan surfaces and in the subsurface revealed by coring. The core hole, from which most of the following alluvial descriptions were taken, was located at 9W6S at the Leaky Acres Recharge Facility in northeastern Fresno (fig. 33) adjacent to Sierra Vista Avenue between Dakota and Ashlan Avenues. Here, all three defined local sedimentary formations were cored to a depth of 105 ft (32 m) with an 80-percent core recovery.

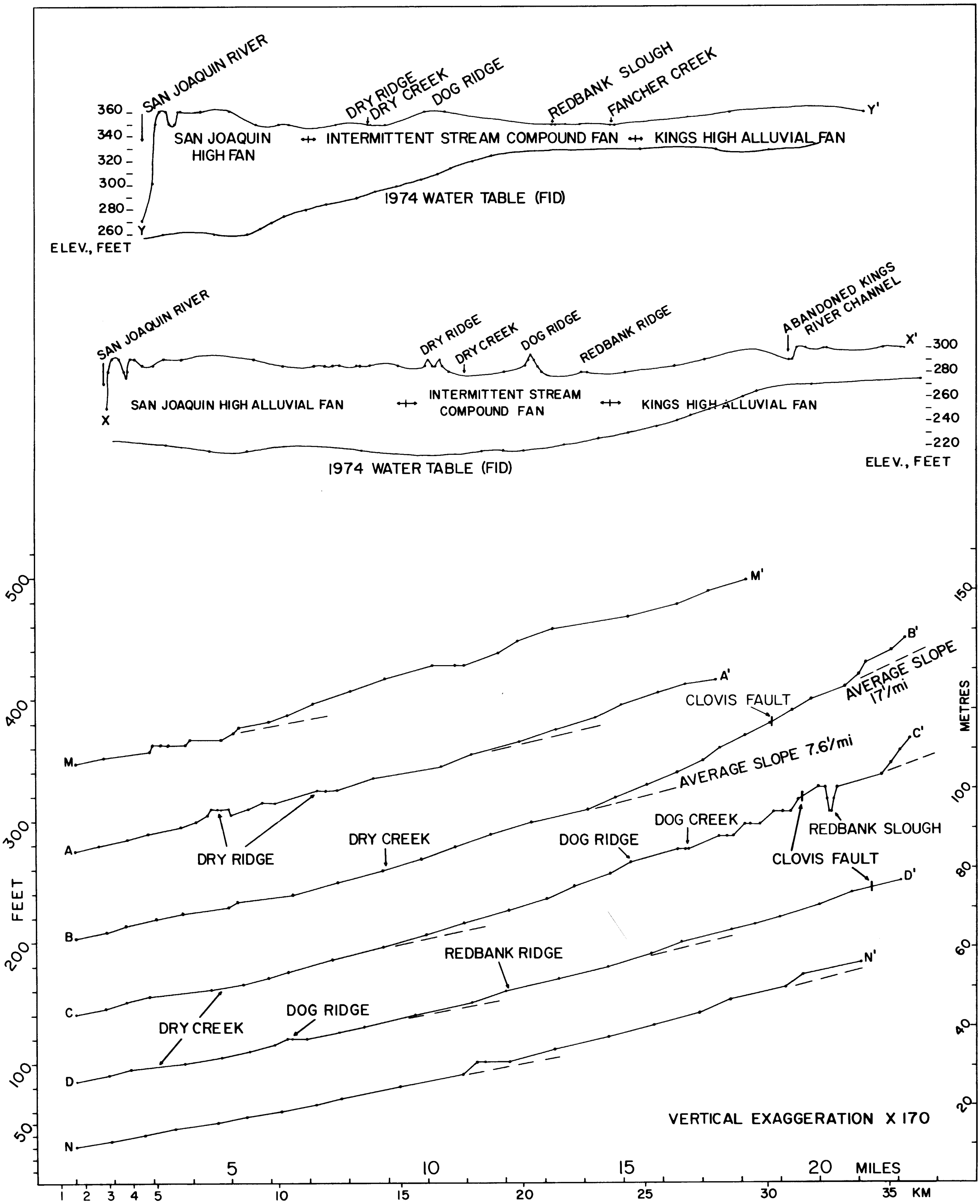


FIGURE 30.—Segmented Fresno fan cross sections located on figure 27. Dashes indicate segment breaks. Cross sections *A*, *B*, *C*, *D*, *M*, and *N* are on the fan radials, whereas cross sections *X* and *Y* are perpendicular to the gradient.

VERTICAL ACCRETION DEPOSITS

Levee and proximal overbank deposits.—Levee deposits and related proximal overbank debris form a large part of the present surface of the Fresno fans. These deposit types account for 47 percent of the core sample and undoubtably much of the subsurface. The deposits are composed of a variety of textures, ranging from poorly sorted silts to clayey fine sand to well-sorted, fine, silty clays (fig. 34) (table 9). They are massive with little, if any, included bedding or other sedimentary structures. In the subsurface, they range from 5 cm to over 500 cm in

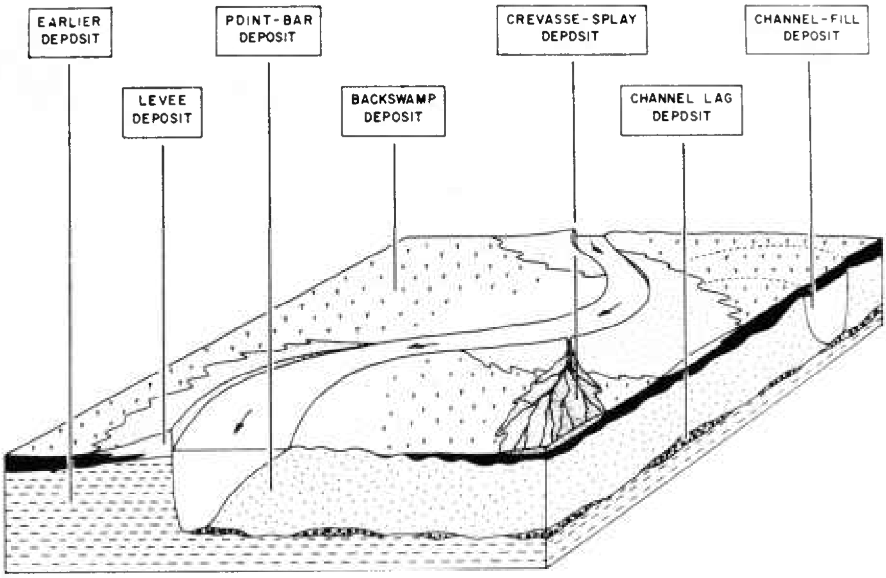
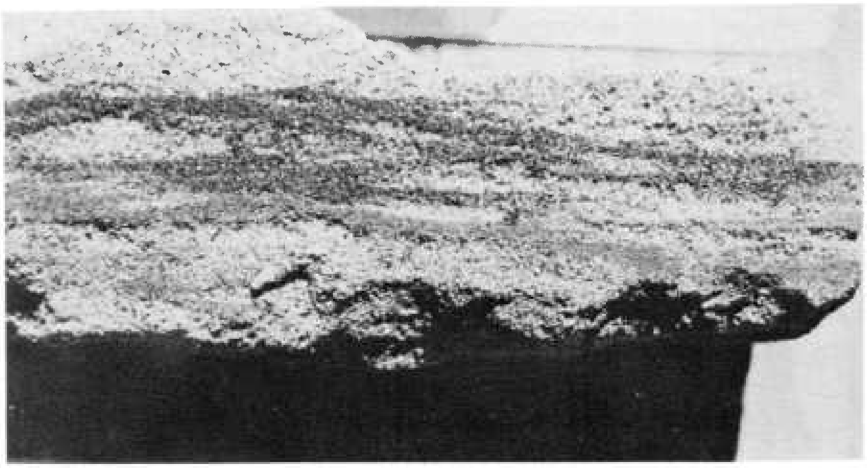
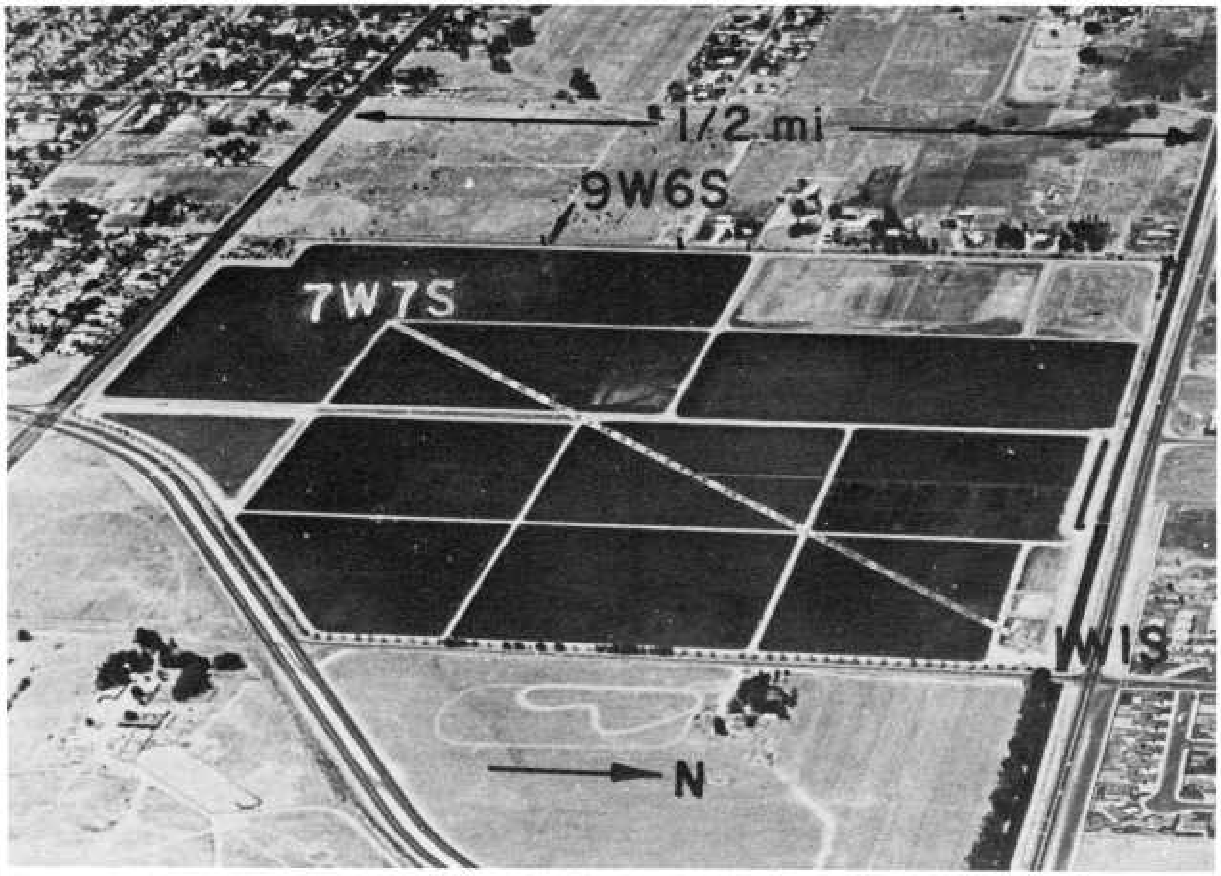


FIGURE 31.—Facies model of the flood plain of a meandering river. From Allen (*1*).



PN–6557

FIGURE 32.—Crossbedding (stratification) from the 68-ft (20.7 m) depth of observation well 7W7S at the Leaky Acres Recharge Facility (fig. 33). Crossbedding is defined by the mineralogical separation of the darker biotite and hornblende from the lighter feldspar, quartz, and lithic fragments.



PN-6558

FIGURE 33.—The City of Fresno's Leaky Acres Recharge Facility looking west. The locations of the 9W6S (Sierra Vista Avenue) core (fig. 54) and cross section (fig. 5) are shown. The facility is bounded by Dakota (S), Sierra Vista (W), Ashlan (N), and Winery (E) Avenues.

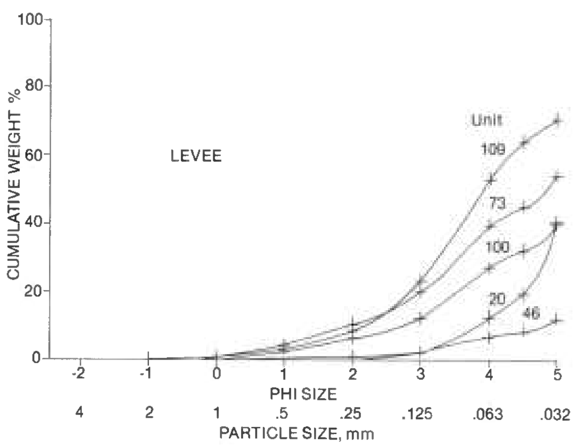


FIGURE 34.—Particle or grain size versus cumulative-weight percent for sample levee deposits. See figure 54 for unit numbers. Unit 109 is from the Riverbank Formation, the remainder are all Turlock Lake Formation sediments.

thickness, indicative of time-varied stream proximity. Levee deposits show gradational, sharp, or erosional contacts; in some instances, a levee sequence is formed by multiple units with sharp depositional or erosional surfaces between successive deposits. If surficial depositional trends present in the core holes continue in the subsurface, then subsurface levee and overbank deposits will be most prevalent in medial and distal portions of the compound fan, generally centered in the Fresno–Clovis metropolitan area.

Within the Riverbank Formation levee deposits, several 1-cm thick red clay lenses (fig. 35) are found with unknown aerial extent. These clays exhibit the best sorting and are the most "plastic" of any encountered. They might represent some form of a late stage, flood settling process that is gradational within the surrounding levee deposits.

TABLE 9.—*Depositional types and textures encountered in the Leaky Acres recharge site core*

Deposit type / Formation / Core unit[1]	Depth	Textural description	Deposit type / Formation / Core unit[1]	Depth	Textural description
	Feet (Meters)			*Feet (Meters)*	
Channel lag deposits			Levee and overbank deposits		
Modesto Formation			Modesto Formation		
114	18 (5.5)	Poorly sorted, gravelly, coarse sand.	Surface sample		Poorly sorted, slightly clayey and silty medium to fine sand.
Turlock Lake Formation			Riverbank Formation		
75	58–61 (17.7–18.6)	Poorly sorted, medium sand.	109	25 (7.6)	Poorly sorted, silty clayey fine sand.
48	75 (22.9)	Poorly sorted, medium sand.	105	31 (9.4)	Very poorly sorted, clayey medium to coarse sand.
Point bar deposits					
Turlock Lake Formation					
78	57 (17.4)	Very well sorted, silty clay.	102	36 (11.0)	Poorly sorted, fine sandy clay.
68	65 (19.8)	Moderately sorted, silty and very fine sandy clay.	Turlock Lake Formation		
			100	38 (11.6)	Moderately sorted, fine sandy clay.
39	82–84 (25.0–25.6)	Moderately well sorted, very fine sandy and silty clay.	92	44 (13.4)	Well sorted, very fine sandy and silty clay.
28	88–89.5 (26.8–27.3)	Moderately well sorted, clayey and silty very fine sand.	73	61–63 (18.6–19.2)	Poorly sorted, silts and very fine sandy clay.
			72	63 (19.2)	Moderately sorted, fine sandy clay.
12	102–103 (31.1–31.4)	Moderately well sorted, fine sandy and silty clay.	46	77–79 (23.5–24.1)	Well sorted, fine silty clay.
Channel bar deposit			20	95 (29.0)	Well sorted, very fine sandy and silty clay.
Turlock Lake Formation					
17	100.5 (30.6)	Well sorted, fine sandy and silty clay.	Crevasse splay deposits		
Channel fill deposit			Modesto Formation		
Turlock Lake Formation			121	9 (2.7)	Poorly sorted, clayey fine sand.
			Riverbank Formation		
44	80.5 (24.5)	Moderately well sorted, very fine sandy and silty clay.	112	20 (6.1)	Very poorly sorted, gravelly clayey medium to coarse sand.

See footnote at end of table.

TABLE 9.—*Depositional types and textures encountered in the Leaky Acres recharge site core —Continued.*

Deposit type Formation Core unit[1]	Depth	Textural description
	Feet *(Meters)*	
Turlock Lake Formation		
97	42 (12.8)	Very poorly sorted, clayey sand.
2	106–109 (32.3–33.2)	Poorly sorted, slightly silty and clayey medium to fine sand.
Flood plain deposits Turlock Lake Formation		
95	43 (13.1)	Very well sorted clay.
36	84–85 (25.6–25.9)	Very well sorted silty clay.
25	95–94 (28.0–28.7)	Very well sorted clay.

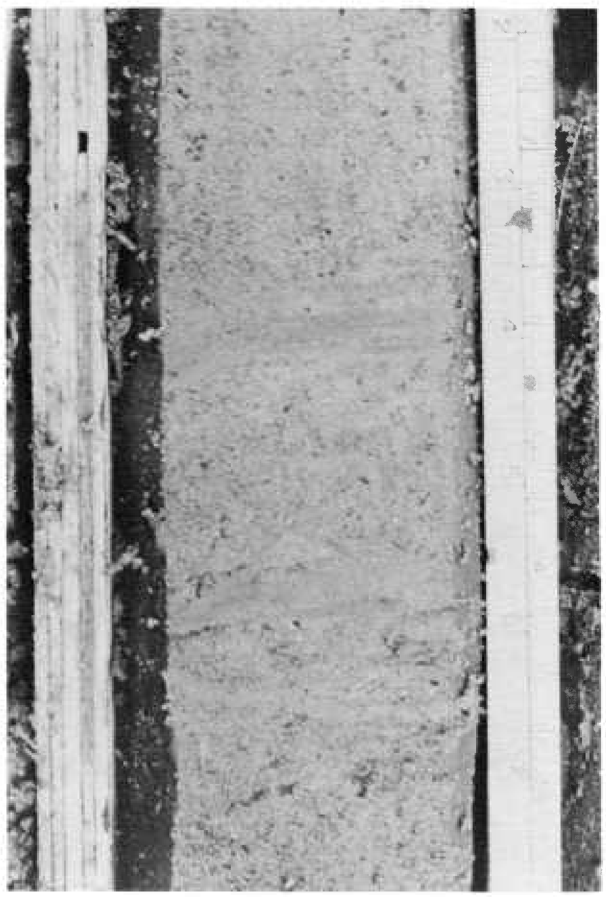
[1] See figure 54, p. 53–57.

Crevasse splay deposits.—Crevasse splays are found as surface and subsurface deposits in the Fresno fans. They show up well in aerial photos as exhibited by Modesto Formation splays (figs. 36 and 37) on the compound fan. In the core, splays form about 5 percent of the total thickness, yet they seem to be more prominent and plentiful on the fan surfaces. Crevasse splay deposits consist of poorly sorted, very fine clay to medium sand in "massively" bedded deposits with no observable sedimentary features. All the splays encountered in the core have thicknesses greater than 25 cm.

Crevasse splay materials are distinguished from levee and overbank deposits (fig. 34) by their larger maximum grain size and total coarser fraction (fig. 38). Generally, they have an erosional lower contact, derived from the larger magnitude crevassing streamflows, whereas the upper contacts can be abrupt or gradational (fig. 39).

The dimensions of surficial splays vary; smaller ones (one mile long) are associated with ephemeral streams, whereas larger splay systems (up to 9 mi (14 km) long) originate from the San Joaquin and Kings Rivers.

Flood plain deposits.—On the surface, only limited areas of the Fresno fans contain flood plain deposits. This is primarily due to the incision of the San Joaquin and Kings Rivers, the major sediment contributors, and because ephemeral foothill streams develop insufficient runoff to form extensive flood plains of their own. The most recent and extensive flood plain deposits are located west in the axial trough of the San Joaquin Valley.



PN–6559

FIGURE 35.—Levee deposits with three 0.5- to 1-cm interstratified flood plain clays (at 10, 14 and 16.5 cm) of core unit 104.

The only surficial clays presently accumulating are in low swales found on the topographically dissected upper fan surfaces northeast of Fresno. In the subsurface, flood plain clays form 12 percent of the total core and consist of well- to very well-sorted clays and silty clays (> 85

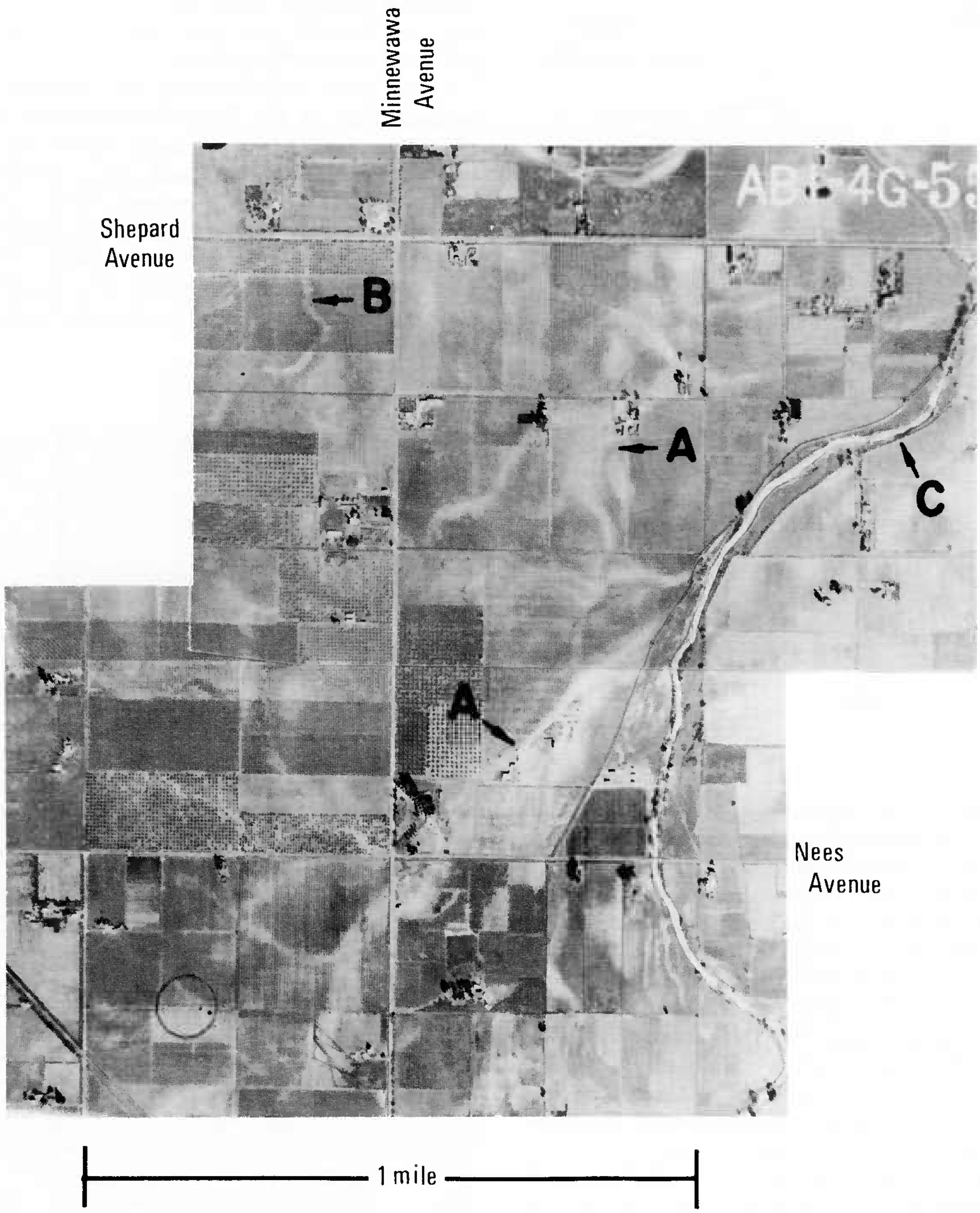


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FIGURE 36.—Surface depositional features: *C*, indicates the current Big Dry Creek channel north of Fresno. Crevasse splays (*A*) are quite obvious in this older airphoto. Distal meanderings of splays (*B*) are much smaller with less extensive coarse grained deposits. (Streets are located on fig. 27).

percent clay) (fig. 40). The deposits range from 2.5 to 62 cm thick, display thin to massive bedding, are either soft and pliable or brittle due to calcium carbonate or silica cementing, and come in a range of colors (pinks, greens, and reds) probably due to (1) irons in differing oxidation states and (2) different postdepositional oxidation-reduction environments. Interestingly, the thinly bedded clays show the greatest color variegation, from pastel pinks and greens to gray; these colors are likely derived from waterlayed and transported volcanic ashes. Some clays display low-angle cross laminations or convolute bedding, the latter arising from soft sediment deformations that include dewatering volcanoes. The first significant clay encountered in the core hole exhibited three to four successive sets of very apparent and well-developed desiccation polygons averaging 2.5 by 1.5 cm with the intervening voids filled by the overlying levee deposit, implying a duration of subaerial exposure. The upper and lower flood plain clay contacts vary from gradational tops and bottoms, the most common, to abrupt bedded surfaces. In some instances, one or both contacts may be erosional.

Within the clays, a significant amount of organic debris is found and is the result of small twigs and branches floating along with the floodwaters and eventually settling on the surface.

LATERAL ACCRETION DEPOSITS

Channel lag deposits.—Channel deposits (Figs. 41 and 42) derived from former stream courses form approximately 10 percent of the core. Because of the core location, the majority of channel lags encountered are derived from ephemeral streams of the compound fan and are not as coarse grained as others encountered in wells penetrating paleo-San Joaquin and Kings River channels. The lags are all poorly sorted

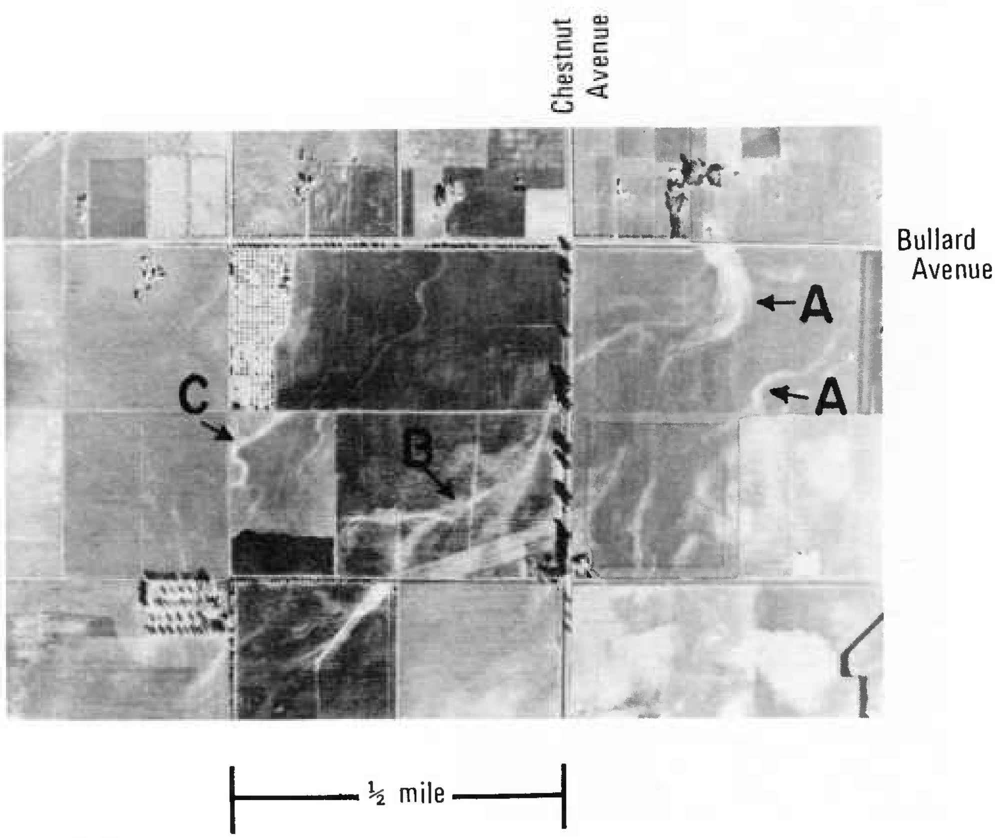

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FIGURE 37.—Former Big Dry Creek deposits: Channel meanders (*A*), crevasse splays (*B*), and small meandering rivulets (*C*) are all obvious features. (Streets are located on fig. 27.)

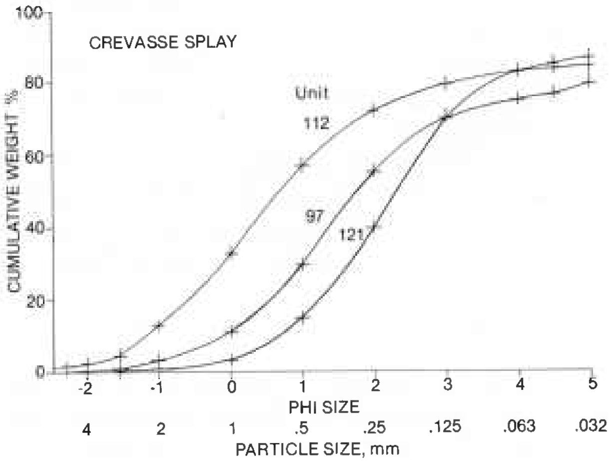

FIGURE 38.—Crevasse splay deposits: Particle or grain size versus cumulative weight percent. (See fig. 54 for unit numbers.) Unit 121 is Modesto Formation, unit 112 is Riverbank Formation, and unit 97 is Turlock Lake Formation. Crevasse splay curves are similar to channel sand curves but with a less radical slope and maximum at the 5-phi increment in the 75- to 85-percent range at 0.032 mm. The crevasse splay and channel sand units were originally segregated on the basis of internal bedding structures.

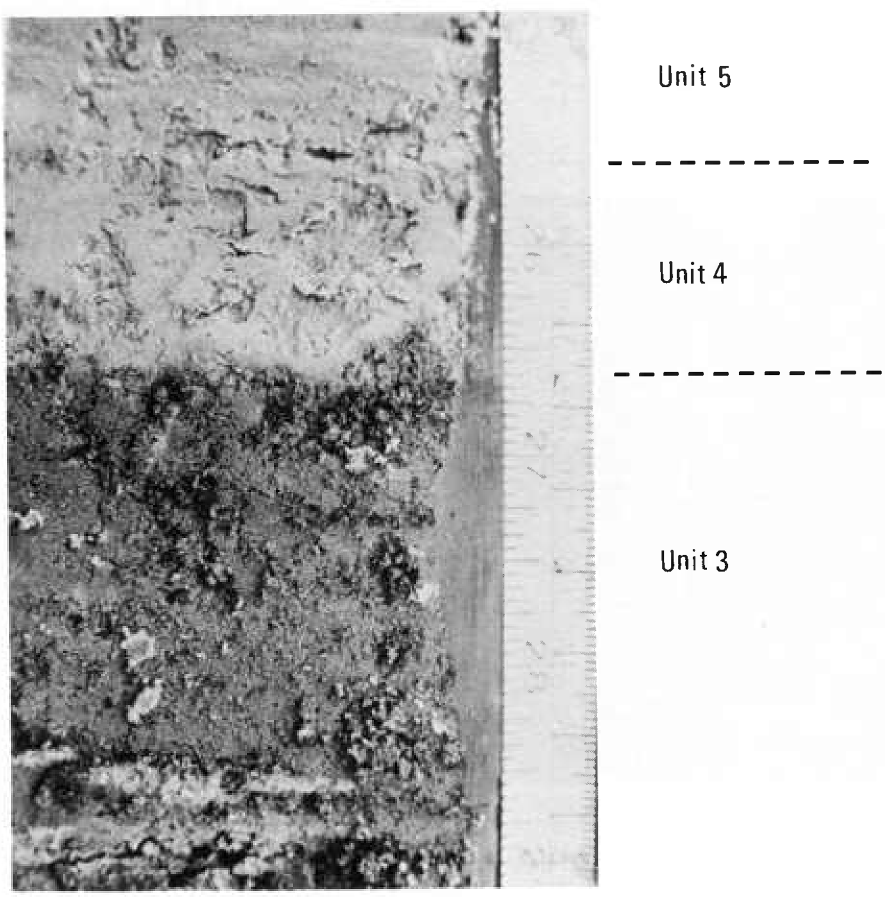

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FIGURE 39.—Sharp contact between a lower green silty fine sandy crevasse splay (unit 3) and an upper light cream and pink sandy silt channel bar (units 4 and 5).

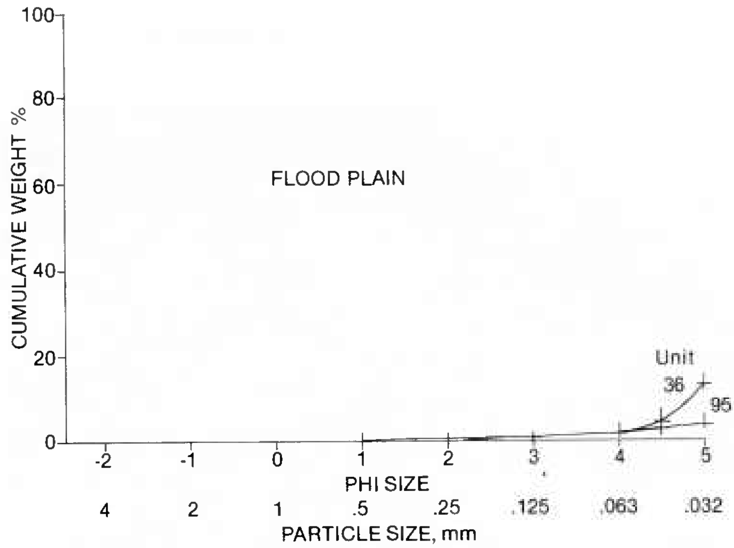

FIGURE 40.—Flood plain deposits—particle size versus cumulative percentage. (See fig. 54 for unit numbers.) Units 36 and 95 are Turlock Lake Formation sediments.

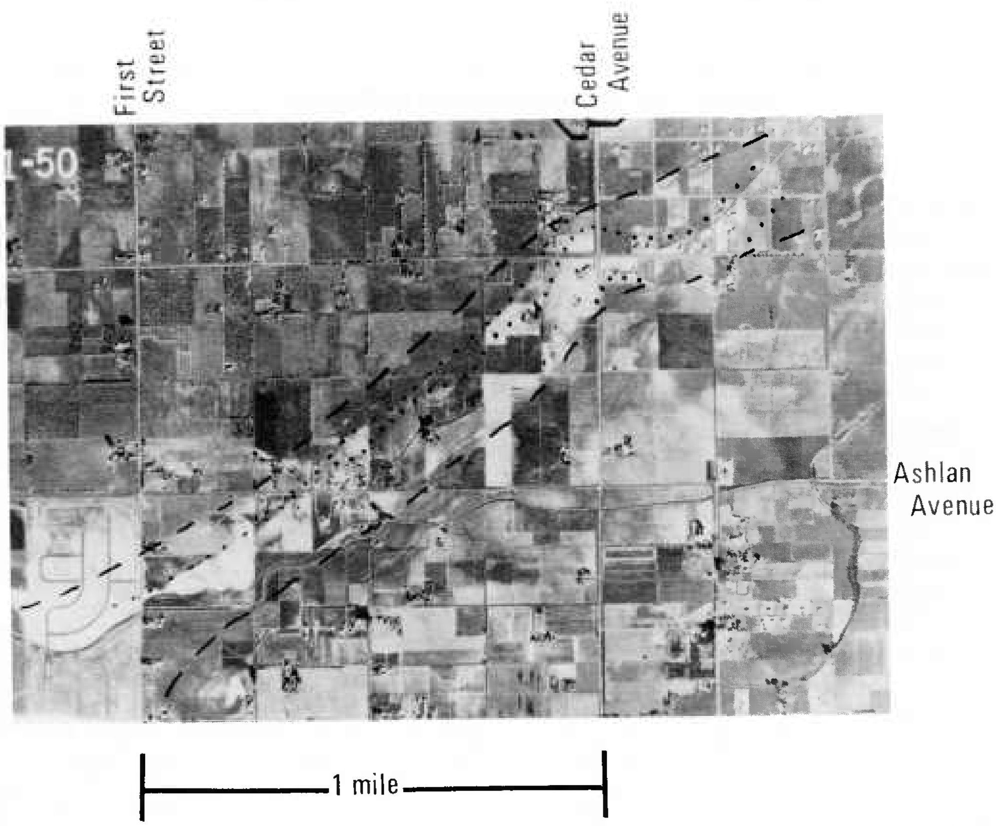

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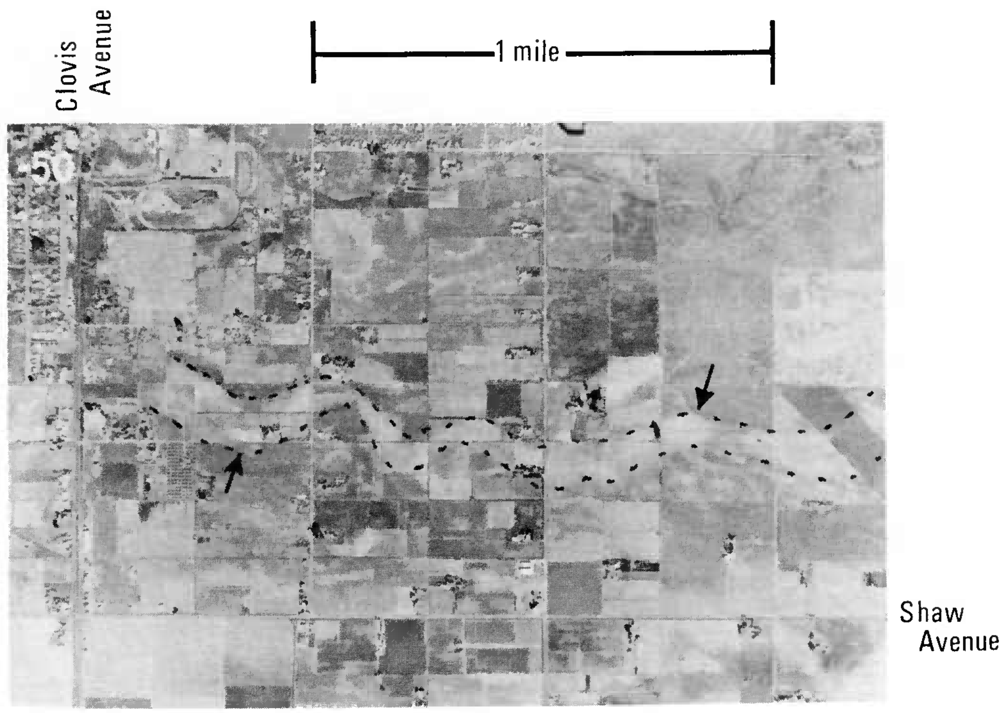
FIGURE 41.—Big Dry Creek channel deposits. Dashed lines indicate channel boundary; the dotted line shows the meandering of the thalweg in the channel. (Streets are located on fig. 27.)



PN–6564

FIGURE 42.—Meandering, abandoned Dog Creek channel deposits, outlined by dotted lines, east of Clovis. (Streets are located on fig. 27.)

and consist of medium sands to gravelley coarse sand (fig. 43). In subsurface San Joaquin channel deposits, extensive gravels are encountered with sizes in the large cobble range (Wentworth scale) (128 to 256 mm); these San Joaquin gravels are present beneath and northwest of Fresno because it appears the river has periodically migrated south and east from its present channel with the fulcrum of shifting in the vicinity of Highway 41 and the present river channel. The cored channel lags of the compound alluvial fans range from 2 cm to over 1 m thick in massively bedded deposits that generally have an abrupt (fig. 44) or erosional lower contact with the upper contact most often gradational.

Point bar deposits.—Point bar deposits are the most abundant of the lateral accretion deposits, 26 percent of the core. They consist of moderately well-sorted to very well-sorted, clayey and silty, very fine sand to fine sandy and silty clays (fig. 45). The deposits vary between 20 cm and 150 cm in thickness. The upper and lower con-

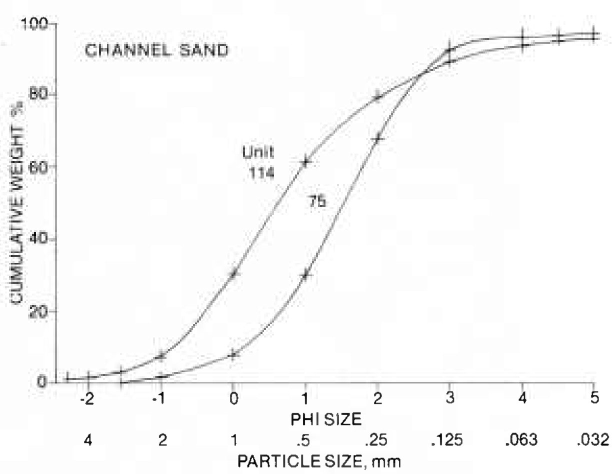


FIGURE 43.—Channel sand (lag) deposits—particle or grain size versus cumulative weight percentage. See figure 54 for unit numbers. Units 74 and 114 are Turlock Lake Formation sediments. The channel sand curves are similar to the crevasse splay curves but with a more radical (steeper) slope and top out in the 90-percent range at 0.032. The channel sand and crevasse splay units were originally segregated on the basis of internal bedding structures.

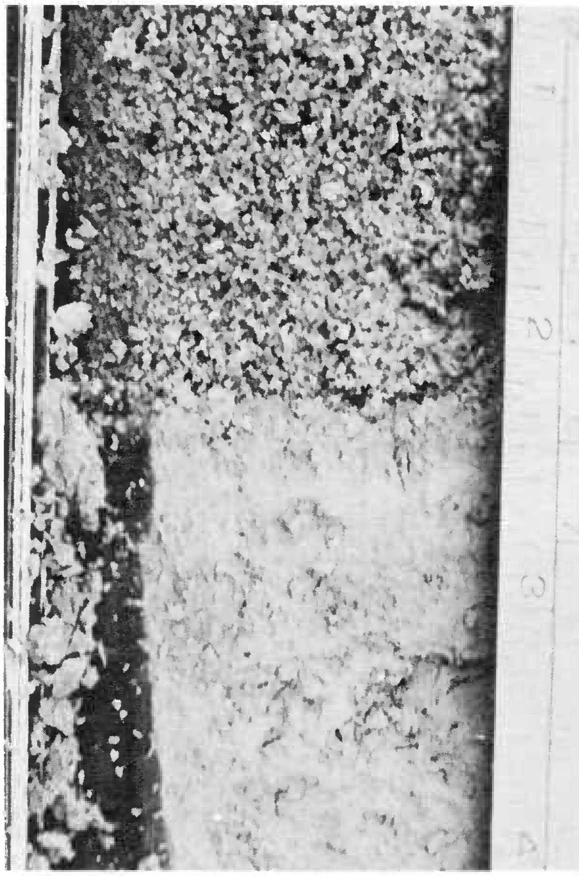


FIGURE 44.—Sharp contact between a lower levee deposit (unit 46) and a coarse sand channel lag (unit 47).

tacts are gradational, abrupt (fig. 46), or erosional with abrupt and erosional contacts between individual beds within the entire point bar deposit. Some erosional surfaces have reliefs of 2.5 cm (fig. 47).

The point bar deposits display a wide variety of color and sedimentary features; like the clays, the colors run the gamut from pastels to grays. The most prominent and common sedimentary feature is crossbedding of several forms: Ripple drift (fig. 48), tabular (fig. 49), or trough. Some of the point bar deposits display a "normal" sequence (*56*) from low-angle cross stratification to ripple drift cross stratification to parallel bedding. In most cases, one or two of these features will be encountered with the rest missing due to nondepositional or erosion. Convolute bedding is also present and is the likely result of overburden loading coupled with thixotropic flow (*19*).

Channel bar deposits.—Channel bars constitute less than 2 percent of the core. This is a result of the intermittent streams and major rivers meandering instead of braiding. The channel bar deposits are well-sorted, fine sandy and silty clays that display distinctive steeeply dipping (28°) avalanche front crossbedding (figs. 50 and 51). Channel bars may have gradational, abrupt, or erosional lower and upper surfaces. The thinly bedded deposits display a variety of pastel colors as well as mineralogic variability within the bedding.

In some instances, a channel bar will be superseded by a point bar sequence, which indicates a stream network shift (*56*).

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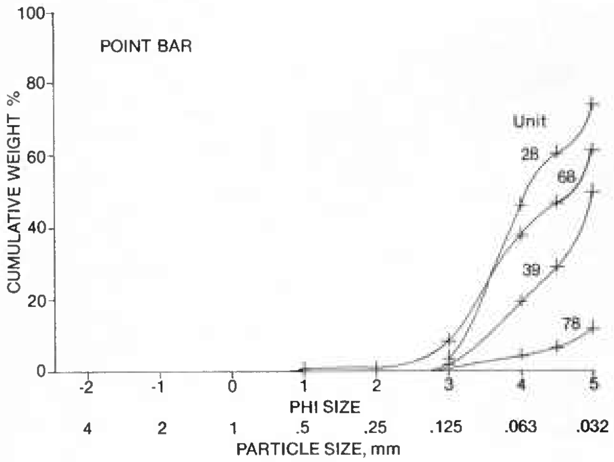
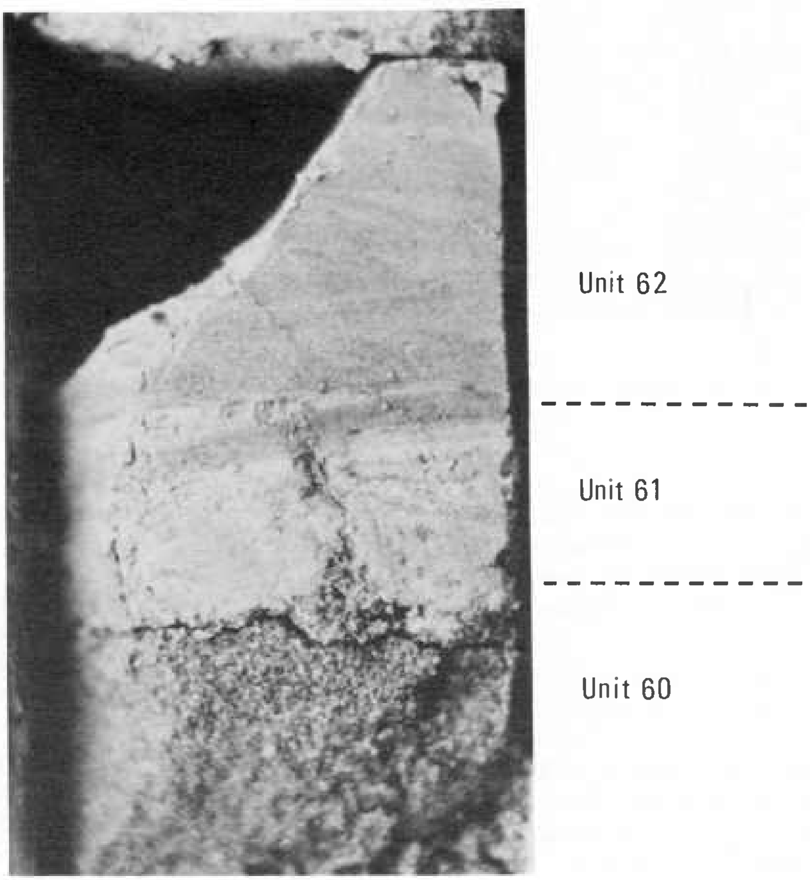


FIGURE 45.—Point bar deposits—particle or grain versus cumulative weight percentage. See figure 54 for unit numbers. All units are from the Turlock Lake Formation. Deposit types and their grain size distributions overlap. Units 39 and 78 are similar to levee deposits but were originally segregated by internal bedding structures.



PN–6566

FIGURE 46.—An abrupt irregular contact between a lower coarse sand channel lag (unit 60) and clay and fine sand point bar deposits (units 61 and 62). Low-angle cross stratification is visible in the point bar units. A small sand dike (injection feature) extends up into the lower clay point bar deposit.

Distribution of Deposits

Alluvial fan deposits are heterogeneous both geomorphically and depositionally. The Fresno fans are no exception as they exhibit great variability through time with a wide variety of depositional processes, alluvial deposits with variable lateral and vertical extents, and multiple source areas and shifting streams to transport, distribute, and deposit material. Therefore, beds on and beneath the Fresno fans are very localized, making stratigraphic correlation of a single depositional layer or group for any distance a difficult to impossible task.

Individual alluvial deposits have vertical and lateral dimensions that vary down fan (proximal to distal) and across the fan. Of the lateral accretion deposits, the channel lags and bars have limited cross fan but greater down fan dimensions. Point bar deposits, more plentiful in the subsurface, will likely exhibit a greater deposit width to length ratio than the other lateral accretion deposits. Of all vertical accretion deposits, flood plains have the greatest areal extents with length to width ratios on the order of 1:1. The levee-overbank dimensions, like the point bars, exhibit greater lengths with moderate widths. The crevasse splays found on the Fresno fans and those described in the literature (2) have a number of narrow anastomosing and bifurcating channels with considerable length. Thus, channel lags and bars and crevasse

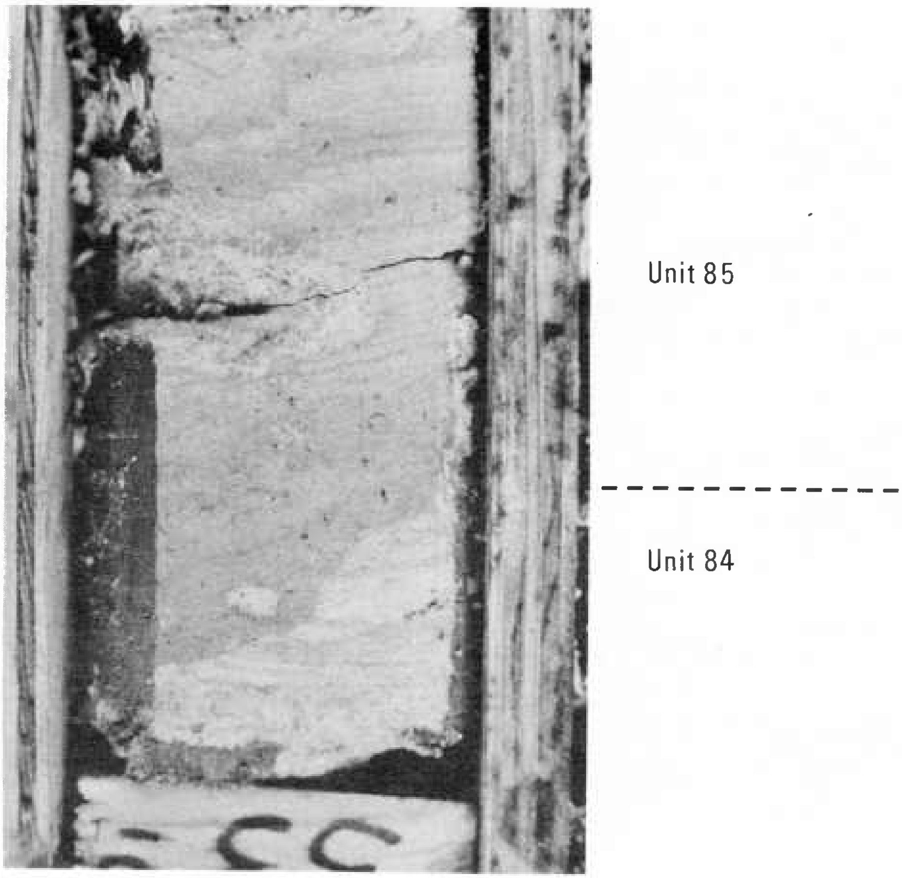


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FIGURE 47.—Erosional contact with 2.5 cm of relief between two point bar deposits (units 84 and 85). Note the inclusion of a piece of unit 84, just above the contact, in unit 85. Both units exhibit crossbedding. At the top of the picture are en echelon slump blocks forming steps within the bedding.

splay deposits will have the greatest length to width ratio, point bars and levee-overbank deposits will have less radical and more moderate length to width ratios, and finally, flood plains will have nearly equal length-to-width ratios.

Even though the Fresno fans surficially and in the subsurface display great variability, certain trends do exist and can be recognized. The coarsest fan material is found closer to the mountain front in association with stream and river channels. Away from the mountain front, finer clay size particles will increasingly predominate in any given deposit type as stream volumes and velocities decrease and as floodwaters spread over the fan surfaces.

In the area between the major drainage deposits (the compound fan surface), a finer total aggregate will be encountered than that obtained from the major rivers. This material, derived from several intermittent streams, becomes finer down fan away from the mountain source area. Yet the coarsest material is confined to narrow channel lag and bar deposits high on the compound fan, and the major volume of sediment here will be fine-grained vertical accretion deposits as there is greater segregation and isolation of deposits with less channel wandering. Lower on the compound fan, the grain size of the alluvium becomes finer (medium to fine sand) with a more uniform aerial distribution, due to increasing down fan channel migrations

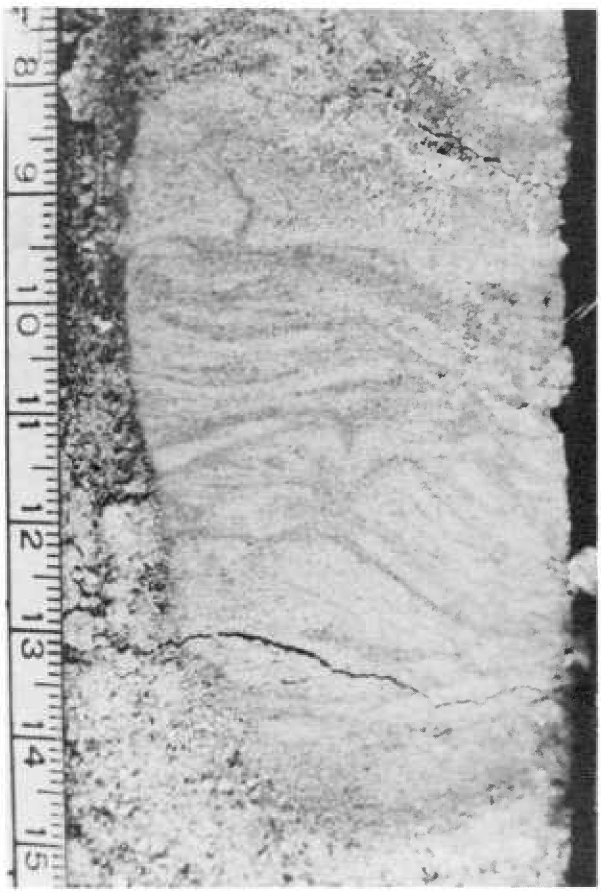

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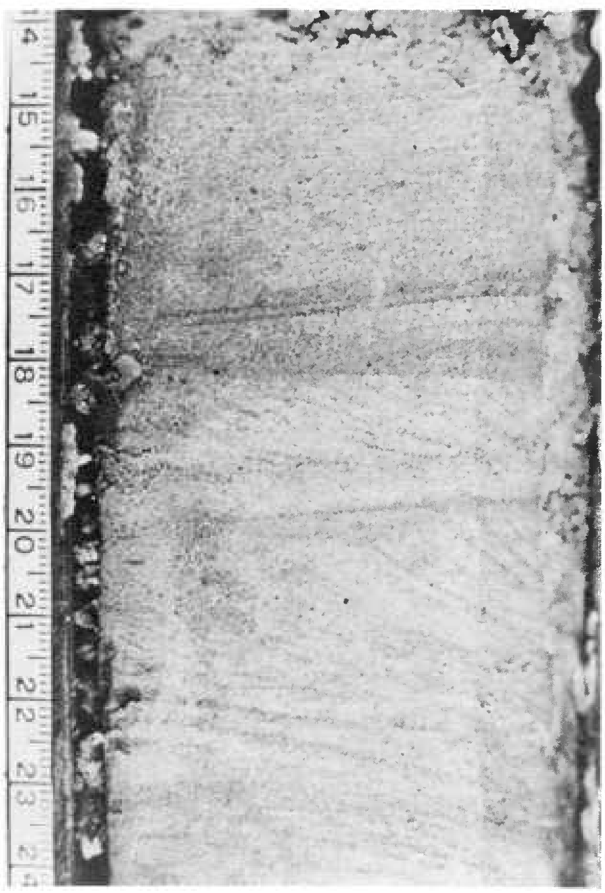
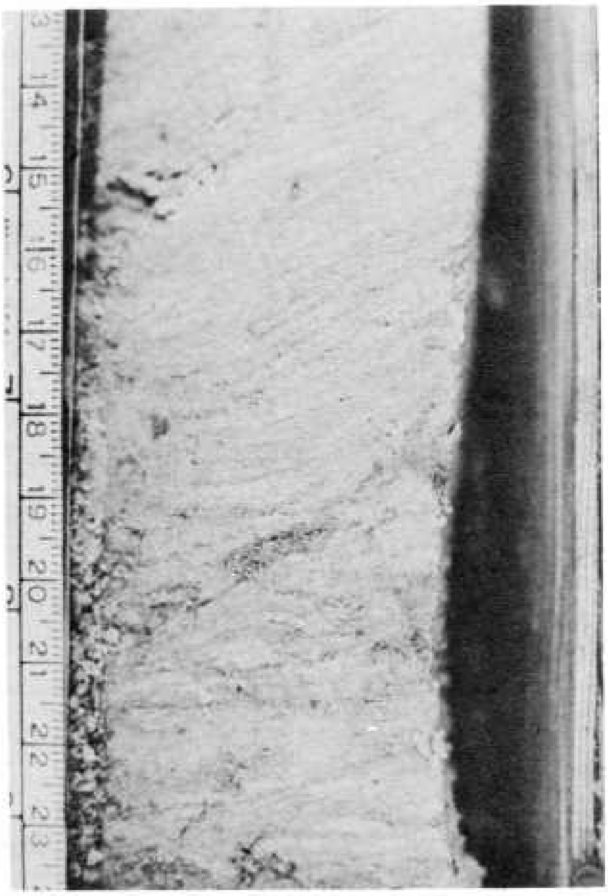
FIGURE 48.—A fine sandy point bar deposit (unit 42) exhibiting ripple drift crossbedding. The lower portion may have undergone some soft sediment deformation.



PN–6569

FIGURE 49.—A fine sandy point bar deposit (unit 62) exhibiting tabular crossbedding sets, defined by specific gravity mineralogical separation of light and dark minerals.



such that more sand-size lateral accretion deposits are encountered versus finer grained vertical accretion material.

The San Joaquin River, now entrenched, was flowing and depositing on the fan surface south of its present location during the Pleistocene. This unconfined, meandering, paleo-San Joaquin was the principal source of the coarser subsurface channel lag gravels (*59*) found below and west of Metropolitan Fresno. To the south, the Kings River similarly influences the subsurface in the southern Fresno area. Shallow chemical evidence (*52*) (fig. 52) indicates the former Kings channel does not differ drastically from the observable abandoned westward flowing surface channels (fig. 27). Vertical accretion deposits, especially flood plain clays, derived from these two major rivers interfinger and coalesce beneath the present compound fan surface.

Farther from the mountain front, the thickness of any individual deposit generally de-

PN–6570

FIGURE 50.—Steeply dipping (28° to 30°) avalanche front crossbedding in a channel bar deposit (unit 17) of fine sandy and silty clay to very fine sand.

PN–6571

FIGURE 51.—Very fine, delicate, tabular crossbedding sets in a very fine sand to sandy silt channel bar sequence (unit 5).

creases, but the number of beds of the same type deposit increases and, thus, bedding surfaces increase. For any time unit, the total thickness of deposits increase away from the mountain down fan, forming a wedge. This process in conjunction with the tectonics of the mountain-valley system (rising mountains adjacent to a sinking trough) through time resulted in the extensive San Joaquin Valley fill.

Formational Geology

The Modesto, Riverbank, and Turlock Lake Formations, all Pleistocene in age (fig. 53), comprise the major surface and subsurface stratigraphic and lithologic units of the Fresno area fans. The Modesto Formation forms a thin veneer associated with the compound alluvial fan of intermittent streams and as westward thickening flood plain deposits in medial and distal locations on the high alluvial fans of the San Joaquin and Kings Rivers, which extend west to the San Joaquin Valley trough. The Riverbank Formation forms surficial deposits on the proximal reaches of the compound alluvial fan and the high fans of the San Joaquin and Kings Rivers. Like the Modesto Formation, the Riverbank Formation is a westward thickening sequence that continues beneath the Modesto. The Turlock Lake Formation is found in the incised San Joaquin River channel bluffs and as isolated outcrops high on the Fresno coalescing fan surface. Even though the Turlock Lake is principally a subsurface unit, it exerts immense influence on the hydraulic and aquifer characteristics in the Fresno area and the San Joaquin Valley.

The soil units in the study area have been mapped by Huntington (*37*) with characteristic soils and soil associations found with each of the formations (*39*) (table 6, p. 9). Because most all of the east side alluvium "is derived from granitic and associated rocks of the Sierra Nevada . . . , the formations offer no textural or lithologic

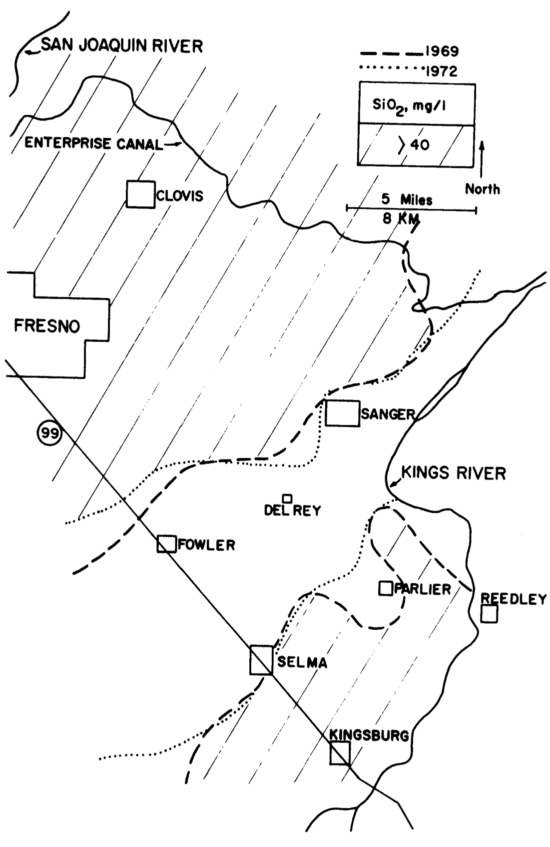


FIGURE 52.—Ground water silica (SiO_2 concentrations) delineates the main portion of the Kings River channel (fig. 27) southwest of Fresno. After Nightingale (*52*).

Age	Formation	Unit	Member
Modern	post-Modesto deposits		holocene IV
Late Holocene			holocene III
			holocene II
Holocene			holocene I
Pleistocene	Modesto Formation		m II (upper)
			m I (lower)
	Riverbank Formation	r III (upper)	
		r II (middle)	
		r I (lower)	
	Turlock Lake Formation	upper	Friant Pumice
			Corcoran Clay
		lower	
Pliocene or Pleistocene	North Merced Gravel		
Late Pliocene	Laguna Formation		China Hat Gravel
Miocene and Pliocene	Mehrten Formation		

FIGURE 53.—San Joaquin Valley alluvial stratigraphy. From Marchand and Allwardt (*44*).

basis for subdivision, . . . nevertheless, the use of formational topographic expression in conjunction with the development of their soils makes it possible to define formations . . ." (*22*).

Distinct and characteristic color changes are associated with the subsurface formational contacts (fig. 5), yet these changes may nowhere near coincide with the formational boundaries or be at equivalent depositional horizons. This is due to differing oxidation-reduction environments. Ordinarily, the Modesto Formation is not cohesive and is dark brown. The indurated sediments begin with the Riverbank Formation, which is a characteristic reddish brown but may vary from yellowish brown to dark brown. The Turlock Lake Formation is predominantly olive gray, yet it displays the widest range in color, especially within the thinly bedded units.

MODESTO FORMATION, INCLUDING POST-MODESTO ALLUVIUM

The Modesto Formation (*22*) and its associated postdepositional alluvium (*45*) comprise the youngest unit of the Fresno fans, cover a large part of the central San Joaquin Valley, and include fan, axial basin, and river channel deposits. They are ". . . associated with the most productive agricultural soils and with areas offering the best potential for ground-water recharge operations" (*39*). In the Fresno area, Modesto sediments are a 10- to 30-ft (3 to 9 m) thick veneer that shows little if any erosional modification and, except for some wind redistribution, the present topographic relief is due primarily to alluvial depositional processes.

The Modesto Formation is a heterogeneous unit composed of a wide spectrum of mineralogies, principally of granitic and metamorphic origins but with some volcanics. It includes a wide range of grain sizes (from clays to granule size gravel) that are generally poorly sorted. Modesto bedding is typically "massive" without any distinguishable gradational intraformational bedding planes.

A mammoth fossil was uncovered during the winter of 1976–77 in the present incised flood plain of the San Joaquin River. It was in the south wall of a gravel pit northwest of the Friant Road and Willow Avenue intersection (T. 11 S., R. 20 E., sec. 36P) 6.5 mi (10.5 km) northeast of Pinedale. Portions of a tusk, fractured skull, jawbone, and a molar were recovered from approximately 8 ft (2.4 m) below the surface (Don Wren, personal commun.). This location is either in the mapped Holocene alluvium of Marchand (*45*) or the underlying upper member of the Modesto Formation. Wren also indicated another large fossil of possibly the same genus was unearthed 20 years ago 150 to 200 yd (137 to 183 m) to the east on the same horizon in another gravel excavation.

RIVERBANK FORMATION

The Riverbank Formation (*22*) comprises the second fan unit, which Janda (*39*) has since modified to include parts of the adjacent Turlock Lake and Modesto Formations. In the Fresno area, the Riverbank Formation is between 15 and 30 ft (4.5 to 9 m) thick, and includes an extensive, though not pervasive, iron-silica hardpan in its upper portions, which is present both subaerially and subsurface. In both positions, it is the first aquitard of the Fresno fan alluvial sequence. The hardpan is associated with the San Joaquin-Ramona-Exeter soil series mapped by Huntington (*37*) and is the only local diagnostic correlative unit within the Riverbank. In the San Joaquin River bluffs (*39*), the Riverbank surface shows moderate modification from ephemeral stream channeling (up to 25 ft or 7.6 m) and gully formation by deepening of previous channels.

The Riverbank Formation is similar to the Modesto in its distinguishable features. It too is composed of heterogeneous sediments that are poorly sorted with a variety of mineralogies, but it exhibits a more massively bedded nature with a few gradational bedding planes.

In the fall of 1975, portions of another mammoth were encountered in a flood control basin at Church and Orange Avenues in southern Fresno. Parts of both tusks, a humerus, six or seven ribs, several vertebras, and a tooth were recovered. A collagen age date was processed in 1976 at University of California, Riverside, giving an age of 19,930 ± 1,500 years before the present (B.P.) (Don Wren, personal commun.). Marchand and Huntington (personal commun.) feel this age should be between 200,000 and 300,000 years B.P. based on the stratigraphy of the fossil location. It is found beneath the Madera hardpan or an equivalent. The bones were buried between 17.5 and 19.0 ft (5.3 and 5.8 m) in Madera Soil Series sediments some 8 ft (2.4 m) below the Modesto-Riverbank contact.

TURLOCK LAKE FORMATION

The Turlock Lake Formation (*22*) is the oldest unit exposed in the Fresno fans and forms extensive and hydraulically important subsurface deposits throughout the San Joaquin Valley. The Turlock Lake, though having minimal surface exposure, is the important time and rock stratigraphic unit of the central San Joaquin Valley basin and fan deposits. Pumice is found in small amounts throughout Turlock Lake deposits. Some concentrated subsurface horizons extend west to the Valley axis where they interfinger with the aerially extensive Corcoran Clay Member of the Turlock Lake Formation. The Corcoran Clay is an important hydrologic, environmental, and correlative unit (both time and stratigraphic) of the axial and western central San Joaquin Valley. This blue-green lacustrine clay defines the upper boundary of San Joaquin Valley aquifers, which were originally artesian (*20*, *21*, *30*). Erosional modifications on the Turlock Lake surfaces include the incision of the San Joaquin River and concomitant gullying of smaller streams through the river bluffs. A swale and gully topography with 20 to 30 ft (6 to 9 m) of relief was formed on the uppermost Turlock Lake deposits (*39*).

Turlock Lake sediments are homogeneous, exhibiting more and thinner bedding (laminated to thick) with gradational, abrupt, or erosional bedding planes. Sorting within a bed will vary depending upon the type of alluvial deposit, but generally the beds show a greater degree of sorting than the Modesto and Riverbank sediments. Better mineralogic segregation within the Turlock Lake Formation is shown by the following sand horizons, encountered in a reverse rotary well at the Leaky Acres Recharge Facility, where the predominant constituents may be volcanic (volcanic arenite), metamorphic (phyllarenite), granitic (arkose), or a mixture (lithic arkose):

Sample depth in feet (and meters)	*Lithology*[1] (*27*)
Surface	Arkose.
57 (17.3)	Do.
73 (22.2)	Volcanic arenite.
82 (25.0)	Do.
97 (29.6)	Volcanic lithic arkose.
102 (31.1)	Do.
120 (36.6)	Metalithic arkose.
125 (38.1)	Do.
140 (42.7)	Do.
141 (43.0)	Do.
152 (46.3)	Metavolcanic lithic arkose.
157 (47.8)	Volcanic lithic arkose.
174 (53.0)	Arkose.
206 (62.8)	Phyllarenite.
208 (63.4)	Volcanic arenite.
219 (66.8)	Do.

[1] Except for the surface sample, which is from the Modesto Formation, all horizons described are from the Turlock Lake Formation. The modifier on the lithic arkose describes the major nonfeldspar (granite) grain type.

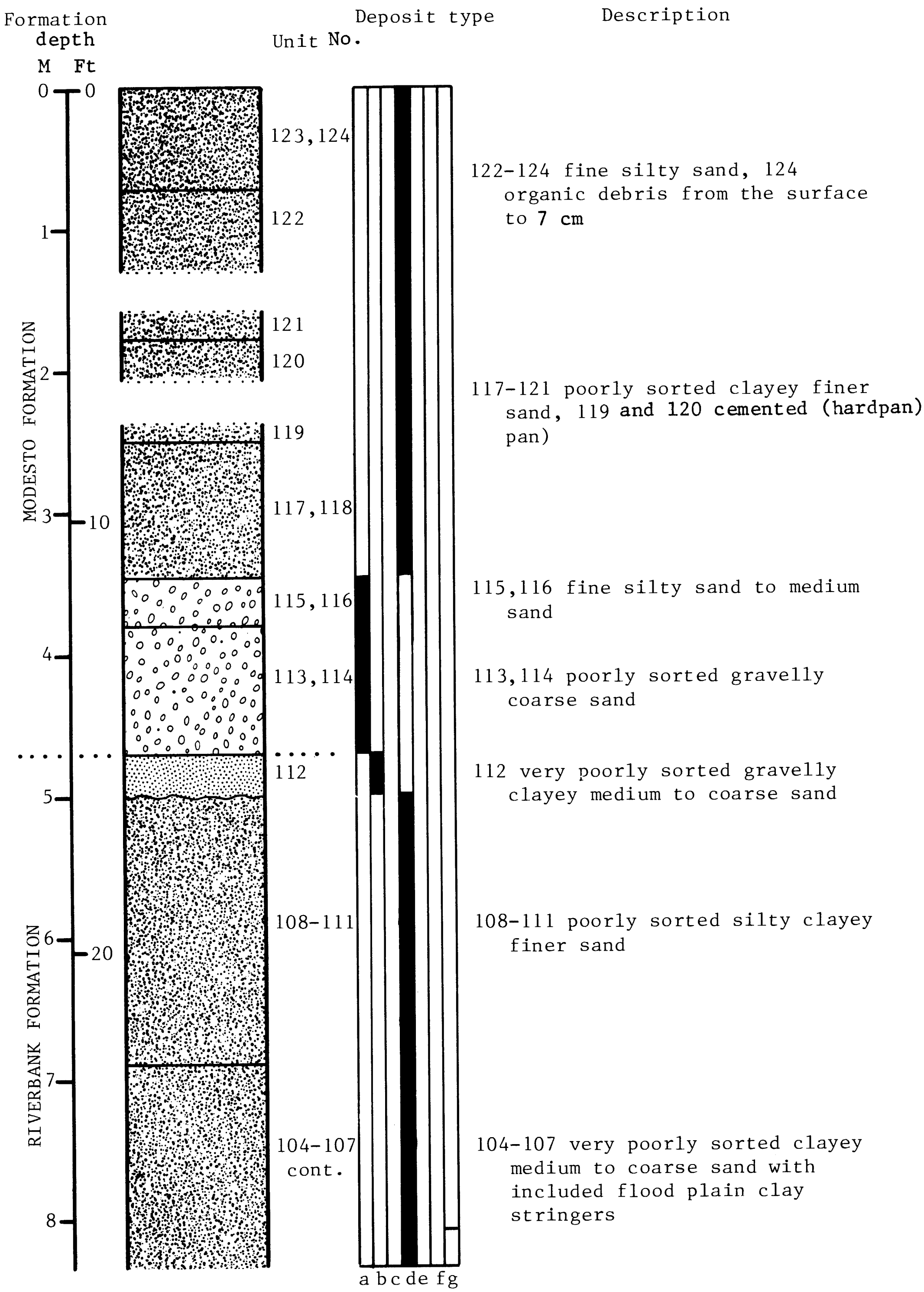
Calcium carbonate cement (**caliche**) has precipitated out and hardened several of the Turlock Lake Horizons. These may be related to paleosoils and surfaces since modified by the overlying deposits.

Diatoms, identified in thin section, have been found in the upper portions of the Turlock Lake Formation. They are most likely freshwater varieties, which lived in streams and lacustrine areas on the fan surface.

Turlock Lake cyclic deposition.—The Turlock Lake Formation is formed by a sequence of cyclic sedimentary units (fig. 54). These cycles are much cruder and not as well defined as those of the Old Red Sandstone in Great Britain described by Allen (*1*, *3*, *4*). Turlock Lake cycles are formed by the shifting of the various compound alluvial fan intermittent streams and the more major wanderings of the San Joaquin and Kings Rivers.

A complete cycle described by Allen would consist of a lower channel lag deposit (former streambed load material), a point bar deposit (sandbar deposit on the inside of a meander loop), levee and overbank material (vertical accretion deposits due to floods), and, finally, an upper flood plain deposit (fine-grained mud and clay deposits). In the Old Red Sandstone,

Text continues on page 57.



Column blanks = unrecovered core
a=channel lag, b=crevasse splay, c=channel bar, d=levee, e=point bar, f=channel fill, g=flood plain

FIGURE 54.—Lithologic column and depositional types encountered in the Leaky Acres Recharge Facility core.

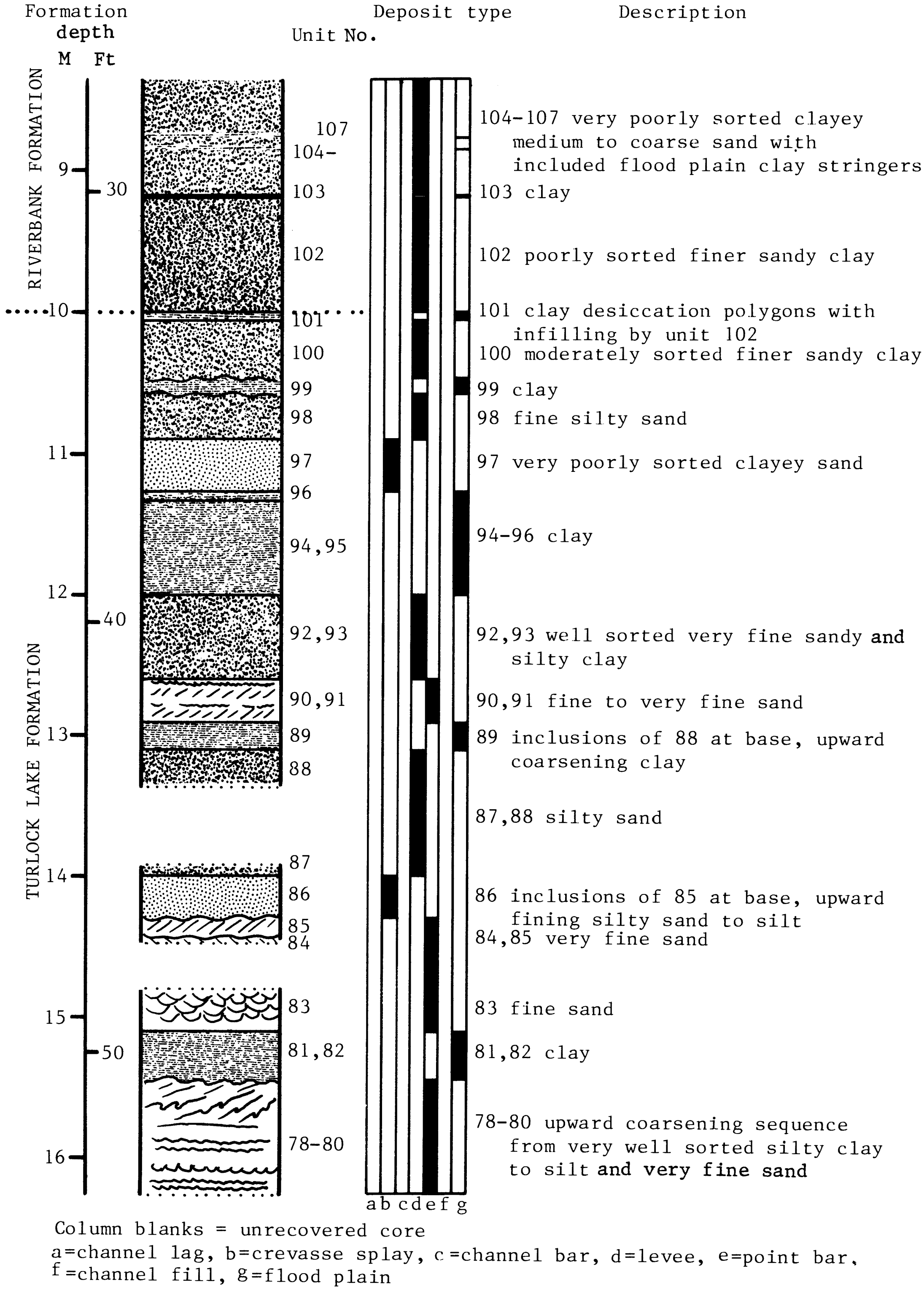


FIGURE 54.—Lithologic column and depositional types encountered in the Leaky Acres Recharge Facility core—Continued.

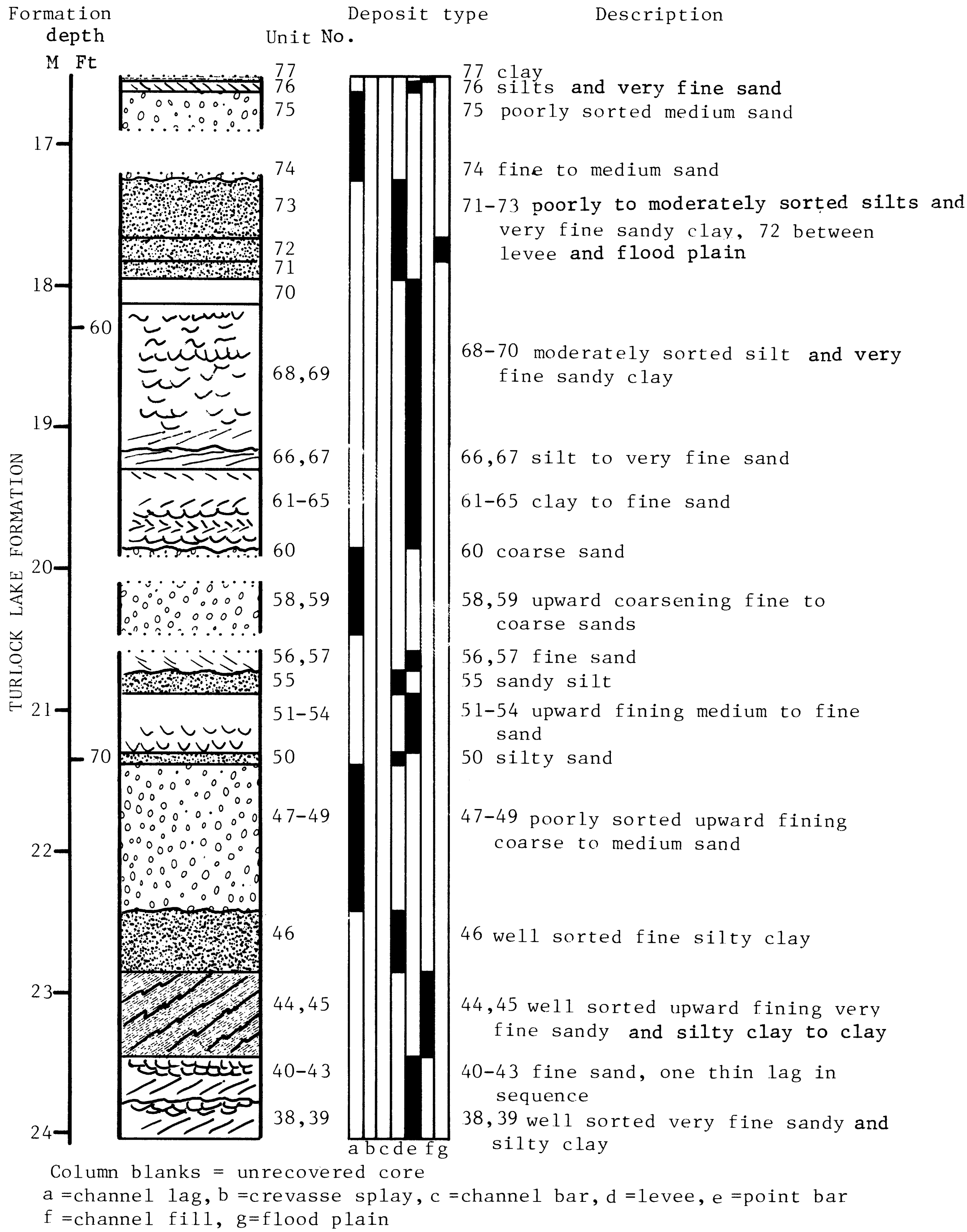


FIGURE 54.—Lithologic column and depositional types encountered in the Leaky Acres Recharge Facility core—Continued.

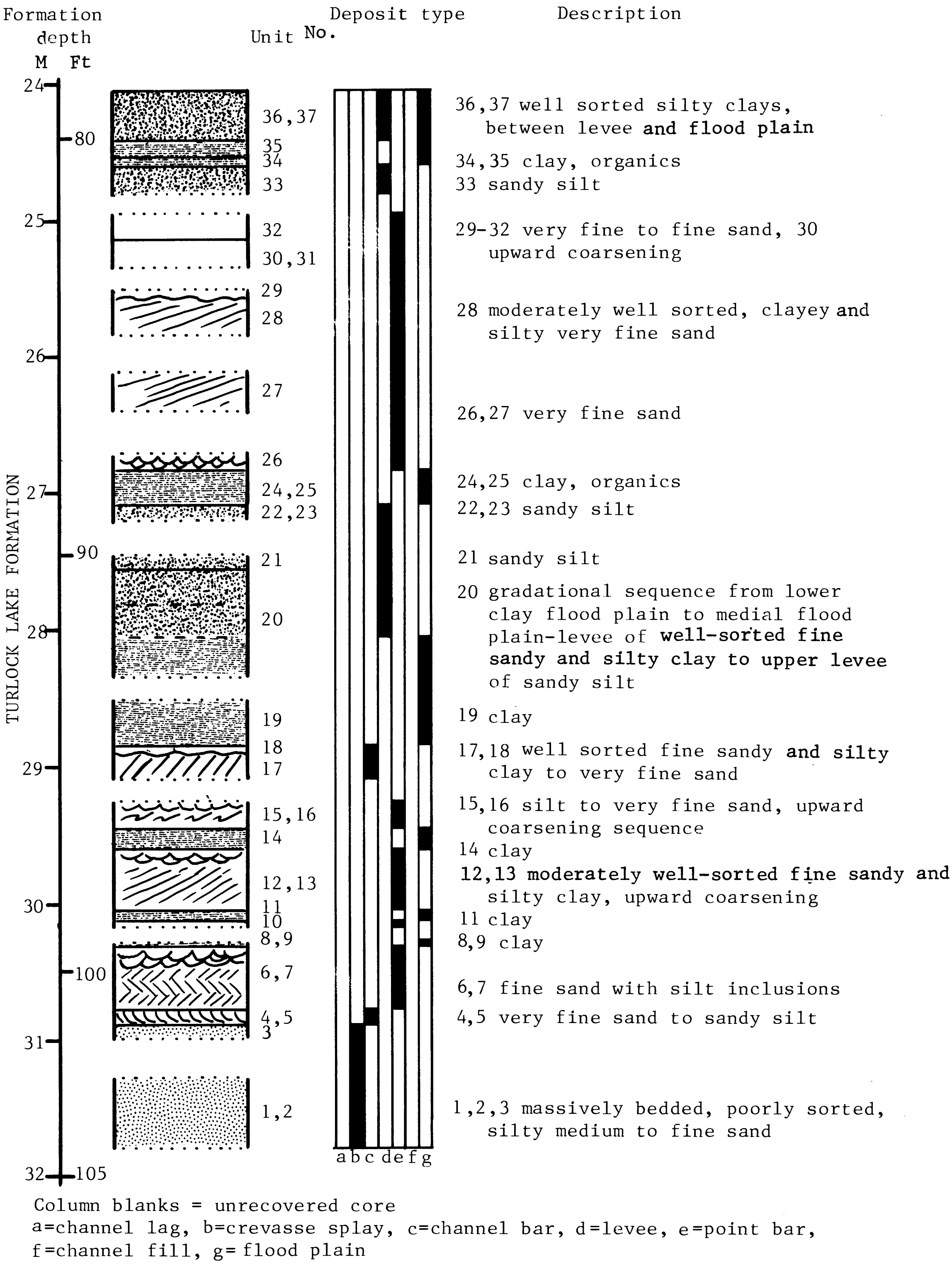


FIGURE 54.—Lithologic column and depositional types encountered in the Leaky Acres Recharge Facility core—Continued.

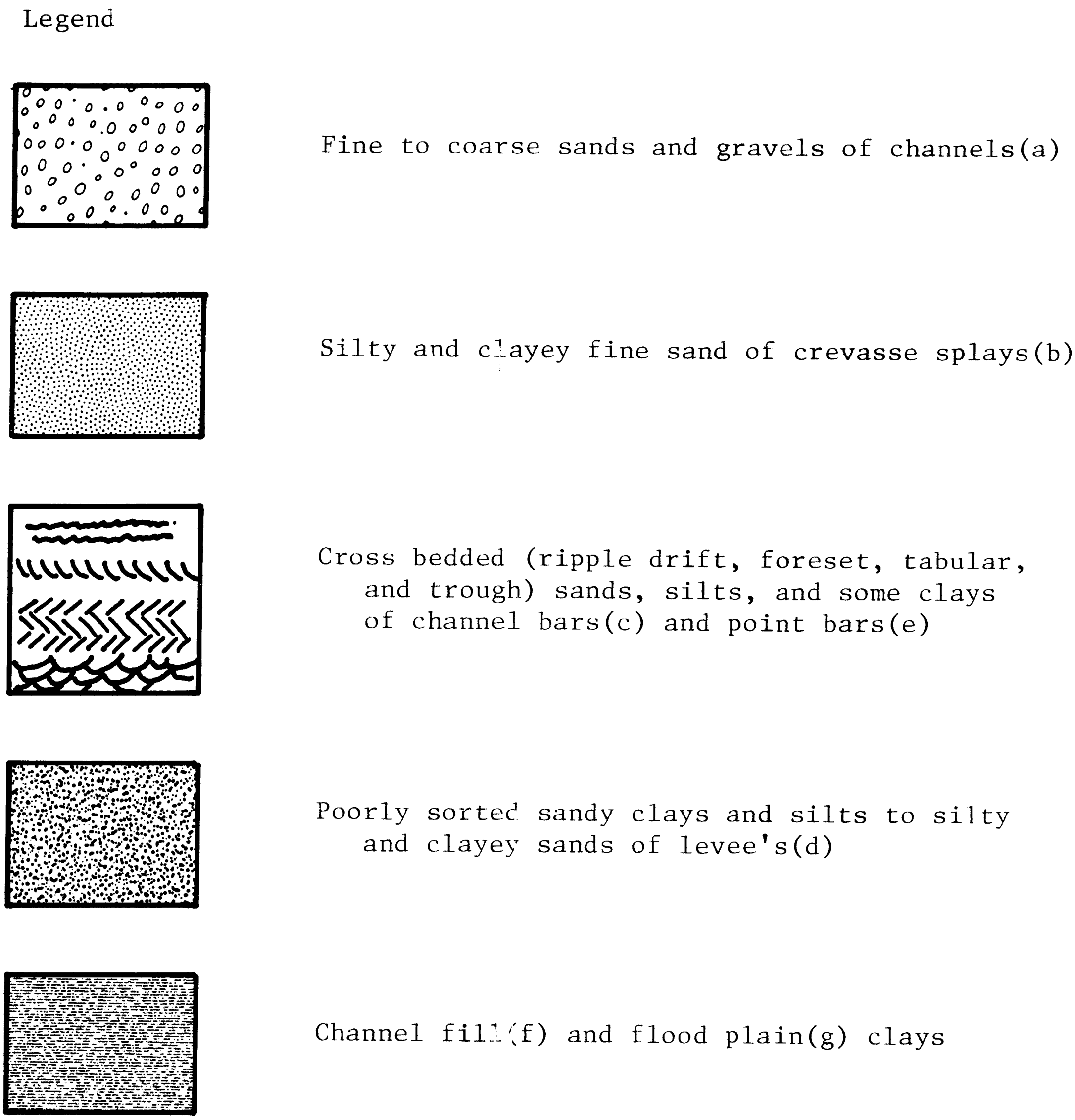


FIGURE 54.—Lithologic column and depositional types encountered in the Leaky Acres Recharge Facility core—Continued.

the cyclic sequences show an upward fining grain size. This does not hold true for the cycles of the Fresno compound fan, as observed in the core. Similarly, Marchand and Allwardt (*44*) reported upward coarsening cycles in all the post-Mehrten alluvial units (Laguna, North Merced Gravel, Turlock Lake, Riverbank, and Modesto Formations) in the northeastern San Joaquin Valley.

The upward coarsening seems to be related to the early Pliocene uplift of the Sierra Nevada and, more importantly, the advances and retreats of the Pleistocene glaciations. In the Fresno fans, it is principally in the point bar and levee deposits that this disparity with Allen's cycles arises, for the point bar deposits are generally finer than those described in the literature, and the levee deposits are a bit coarser than those in the literature, so there is little grain size difference between them (table 9). This may be due to the smaller volumes and velocities of the ephemeral streams and the transport distance (10 to 20 mi or 16 to 32 km) from the mountain front. No complete cycles like Allen's are encountered in the 9W6S core, but occasionally some are nearly complete with normal and expected variable interruptions in the proper sequence. Dickenson (*23*) postulated that a complete uninterrupted cycle would give an indication of the channel depth and width of the paleostream. Some of the thinner cycles found in the Fresno compound fan would then indicate a channel depth from 5 to 8 ft (1.5 to 2.4 m), which is closely analogous to the present intermittent stream channels coursing the fan.

The probable reason for only the Turlock Lake Formation exhibiting cyclic sequences has to do with the relation between the Sierran glacial events and the related fluvial deposition of the glacial materials.

Turlock Lake lithologies.—The following Turlock Lake lithologies and one Modesto lithology (p. 51) were derived from the major sand horizons encountered in a 250-ft (76 m) deep reverse rotary well in the compound alluvial fan at the Leaky Acres Recharge Facility in northeast Fresno. The samples are biased as the fine grained material was lost in drilling. The recovery sample was split into a greater-than-2-mm fraction and a 1- to 2-mm fraction with anywhere from 100 to 600 lithologic counts taken on each grain size.

The lithologies encountered in the Fresno fans reflect their provenance basins: The San Joaquin River drainage (1,750 mi^2 or 4,532 km^2) and the Kings River drainage (1,720 mi^2 or 4,455 km^2), both of which reach the crest of the Sierra Nevada, and a smaller range front drainage of intermittent streams (118 mi^2 or 306 km^2), which includes the Academy Pluton, thoroughly studied by Mack et al. (*43*). The principal rock types encountered consist of the Mesozoic plutonic rocks of the Sierra Nevada Batholith, ranging from alaskite to quartz diorite with quartz monzonite and granodiorite predominant (*6*, *7*). Basic intrusives (gabbros) and ultrabasic rocks are encountered along the western margin of the batholith. The sedimentary and volcanic metamorphic rocks (Paleozoic and Mesozoic) within the source area may be lumped into two major groups: (1) A western set of discontinuous roof pendants, which is the southern extension of the Western Metamorphic Belt; and (2) a second set of pendants located near the crest of the Sierras. Tertiary and Pleistocene volcanic rocks are encountered in both the San Joaquin and Kings River drainages, with greater aerial coverage in the San Joaquin drainage. The volcanics extend from the western Sierra margin to the range crest (*36*) 62 mi (99 km) away. A sizeable volume of glacial deposits is in the source area, generally south of the Middle Fork of the San Joaquin River and north of the Middle Fork of the Kings River between 7,000 and 9,000 ft (2133 to 2743 m) (*46*).

Grains derived principally from the granitic terrain include quartz, the predominant grain, which may be clear to opaque and generally has a pink hematitic(?) outer stain; granitic rock fragments with variable grain sizes (fine to medium) and compositions including graphic granite; and feldspar, principally orthoclase with smaller amounts of plagioclase. The orthoclase may be found as weathered out euhedral crystals or rounded abraded grains. The minor constituents include hornblende and mica, mainly phlogopite with some biotite and muscovite.

Grains that are in part indicative of an ultrabasic origin include hypersthene-enstatite, diopside-augite, olivine, and pyroxenite.

Grains of metamorphic origin include hornfels, schists, gneisses, metavolcanics, skarn, phyllite, metaquartzites, cordierite, actinolite, garnet, epidote, idocrase, glaucophane, diopside-augite, and hypersthene-enstatite.

Volcanic grains include very fine to coarse-grained tan ash; medium- to coarse-grained tuff breccias; pumice, generally pink; rhyolite; and latite. A complete spectrum of volcanic processes and associated rocks is represented. Basalts are noticeably rare.

Volcanic grains form an important and integral part of the Turlock Lake Formation sediments. Volcanic grains, in particular some of the pumice, enable regional stratigraphic and time correlations to be made among the San Joaquin Valley sediments, the volcanic suites of the high Sierras, and the timing of some of the Sierran glacial events.

Janda's (*38*, *39*) age date of the Friant Pumice (ash) Member of the Turlock Lake Formation has been instrumental in decifering the Sierran glacial and stratigraphic timing. The Friant Pumice, dated at 600,000 ± 20,000 years, has been correlated with pumice that interfingers with the lacustrine Corcoran Clay Member of the Turlock Lake Formation and found in the axial portion of the San Joaquin Valley. The probable origin of the pumice and other associated volcanic material is the Quaternary Devils Postpile volcanic suite, situated on the crest of the Sierra Nevada some 60 mi (97 km) east, with part of it in the San Joaquin River drainage. From the observed grains, it is apparent that a considerable portion of the alluvial deposits under northern Fresno originated from the Devils Postpile suite even though other late Tertiary and Quaternary volcanic sources are scattered throughout the San Joaquin and Kings River drainages; these other sources consist almost wholly of basalts and trachybasalts, but very little if any of this basaltic material has been observed from subsurface samples in northern Fresno.

The age of the Devils Postpile volcanic suite (3.1 million years to recent) fits the upper portion of the San Joaquin Valley alluvial sequence and the tectonic movements of the Sierra Nevada, which has affected the channel courses of the major river drainages and their erosion of the volcanic and granitic material (*7*). Janda (*38*, *39*) and Bateman and Wahrhaftig (*7*) have used this and other information to correlate the alluvial formations of the San Joaquin Valley with the Sierran glacial epochs as well as putting an absolute time to the deposition of some of the units.

Relation of Glacial Events and Types of Alluvial Deposition

Janda (*39*) described the geologic history of the San Joaquin Basin and its related San Joaquin Valley alluvial deposits, specifically with respect to the Pleistocene glaciations of the Sierra Nevada. The three formations in the Fresno fans show some major depositional differences with homogeneity between beds and internal grain size heterogeneity within beds in the Modesto and Riverbank sediments. The Turlock Lake sediments display thinnner more heterogeneous beds, with sharper bedding planes, and more homogeneous grain sizes within the individual beds. The Turlock Lake also displays better mineralogic segregation by beds as witnessed in the lithologies encountered.

These sedimentary dissimilarities are related to differences in the various Sierran glacial events and their succeeding interglacial periods. The Turlock Lake Formation has been correlated with the Sierran Hobart glaciation (*7*, *39*), which may correspond to the Kansan continental glaciation (*61*). Turlock Lake Formation beds display more homogeneous grain sizes, reflecting the processes in which, and amounts of material, the Hobart glaciers were eroding and releasing to the fluvial regime. Thus, the Turlock Lake Formation may represent a more consistent continuous release of glacial material to the source basin streams. Mineralogic variability indicates, in part, that a particular source area rock type was undergoing glaciation and release to the water courses. Grain size segregation would be the result of typical fluvial processes dependent upon normal annual stream volume and velocity variation. The better defined, more regular bedding is the result of greater annual stream releases and more stream meandering than that occurring at present.

Matthes (*46*) indicated that the pre-Wisconsin glaciations were of a larger magnitude and greater areal extent than the Wisconsin glaciations. These early glaciers were also extant for a longer period. The Turlock Lake sediments may thus indicate typical glacial advances and retreats, not extreme fluctuations, but, more importantly, they indicate an almost continuous volumetric input of glacial and morainal debris to the outwash regime.

The Riverbank and Modesto Formations exhibit a different type of sediment input to the fluvial system as shown by their heterogeniety, massively bedded nature, and poor mineralogic segregation. The Riverbank sediments have been correlated with the Donner Lake glaciation of probable Illinoian continental association (*61*), whereas the Modesto Formation sediments are derived from the Tioga, Tenaya, and Tahoe Sierran glaciations correlative with the Wisconsin continental glaciation.

The glaciations responsible for the younger Riverbank and Modesto Formations did not introduce sediment into the fluvial outwash stream system in the same manner as that encountered in the Turlock Lake Formation. These later glaciations were of a smaller extent and duration, but from the style of their sedimentary deposits it appears that the introduction of fluvial sediments by these glaciations was in large pulses or slugs with a greater variety of grain sizes and mineralogies admixed with little alluvial segregation occurring during transport to the San Joaquin Valley. These later glaciations and their outwashes probably were also reworking older morainal material, resulting in greater hetrogeneity of material. Some possibilities for larger pulses and influxes of sediment to the outwash regime may be due to rapid melting associated with glacial retreats or temporary ponding of glacial outwash behind moraines that may have breached, releasing a large admixed sediment load into the fluvial system.

Thus, the differences in the sizes, durations, and fluctuations of the Pleistocene glaciations and how their glacial outwash and morainal material was released and washed into the fluvial system of the San Joaquin Valley account for the variations observed in bedding, sorting, and lithologies of the different alluvial formations. The Turlock Lake Formation indicates longer term, more stable glaciation events, whereas the Riverbank and Modesto Formations are due to shorter term glacial events with more radical fluctuations, giving rise to larger pulses of sediment introduced rapidly into the fluvial system.

Geomorphic Divisions

The surface of the study area has been divided and defined by Page and LeBlanc (*55*). These major breakdowns (figs. 27 and 30) are based on the topographic and depositional expressions of the coalescing alluvial fans formed by the preincised San Joaquin and Kings Rivers and by the intermittent streams on the compound fan. Because of watershed size differences and source rock availability differences, different sediment types and deposits may be found on each of the fans.

HIGH ALLUVIAL FAN OF THE SAN JOAQUIN RIVER

The San Joaquin high alluvial fan is the northernmost fan in the Fresno area. It has no active stream on its surface because both the San Joaquin River and Little Dry Creek channel (not shown on fig 27) are incised, leaving only small amounts of surface runoff crossing the fan to the south. The San Joaquin fan displays a gently concaved, segmented radial profile with its apical end at 450 ft (137 m) elevation, whereas some 20 mi (32 km) downfan, the elevation is 250 ft (76 m), resulting in a 10 ft/mi (1.9 m/km) average gradient. A cross fan profile (fig. 30) shows a convex surface from the bluffs on the incised San Joaquin River down an irregular slope, produced by depositional features, to its intersection with the adjacent compound fan.

Morphologic and topographic features that predominate on the San Joaquin fan include (1) a "hogwallow" topography (*5*) associated with the mima mounds of the San Joaquin-Ramona-Exeter soil series hardpans, and (2) large channel and ridge deposits originating from San Joaquin River crevasse splays. Mima mounds, whose origins are debated, are found on flatter fan surfaces; so many locations have been leveled for agriculture and urban expansion, the best remaining mounds are on the San Joaquin River bluffs.

Crevasse splays are expressed both as prominent channels and ridges or as subdued weathered and eroded depositional ridges and splays. The most prominent splay system is at Herndon Avenue and Highway 99 with an incised channel 15 ft (4.6 m) deep, showing relict stream channel and bar features. This particular splay is traceable for over 9 mi (14 km) to the south with distributary channels and associated channel-ridge and flood plain deposits encountered after 5 mi (8 km). East of Highway 99 are shorter (4 mi, 6 km), broader, lobate distributary splays with less than 5 ft (1.5 m) of relief on the channel and ridge deposits. In all cases, the San Joaquin high fan splay channels and ridges trend southwest to south-southwest.

COMPOUND ALLUVIAL FAN OF INTERMITTENT STREAMS

The compound alluvial fan (figs. 27 and 30) is formed by deposits derived from four ephemeral streams: Dog, Big Dry, and Fancher Creeks and Redbank Slough; all have seasonal discharges several orders of magnitude smaller than those of the perennial San Joaquin and Kings Rivers. Since the early Holocene(?) incision of the San Joaquin River (85 ft, 26 m) and Kings River (20 to 30 ft, 6–9 m), the intermittent streams are the only active water courses transporting and depositing alluvium on the Fresno fans. Narrowing basinward from a wide multiple-entry apex, the compound fan shape is confined and controlled by the extents of the adjacent San Joaquin and Kings Rivers high alluvial fans.

The coalescing boundary between the San Joaquin high fan and the compound fan is sharply defined, whereas an irregular interfingering boundary relationship exists with the Kings River high fan. The compound fan gradient averages 14.6 ft/mile (2.7 m/km) over its 26 mi (42 km) length from the Big Dry–Dog Creek reentrant to its toe.

Today, streamflow on the compound fan surface is no longer down the fan radials. The three northern streams (Big Dry, Dog, and Redbank) have undergone a recent (Holocene) southern channel avulsion. Both Big Dry and Dog Creeks leave their former channels on the upper fan, whereas Redbank Slough leaves its old channel halfway down the fan. These streams now flow in the depressions between their old channel and the next relict channel south with only small amounts of recent alluvium deposited along their new courses. Dog Creek and Redbank Slough now join Fancher Creek (the southernmost stream) in the south-central portion of the fan. This downgradient confluence of streams may be governed by several factors: Normal stream avulsions, the relative size, shape, and gradient of the adjacent fans, and tectonic movements (tilt and uplift) of the fan itself, that is, a fault scarp crossing the fan head (*54*) (fig. 55). The most recent avulsion (the abrupt desertion of an old stream course for a new one) of the three northern streams occurs down-gradient on the down-dropped side of a small range-front fault crossing the head of the compound fan. The southernmost stream remains in its channel close to the Kings fan and thus may be regulated by the Kings' fan height and unable to shift south as did the other stream.

The most prominent topographic and physiographic features on the compound fan surface are three major and several minor stream channel ridges (fig. 27). The northern ridge is a product of Dry Creek; the central, of Dog Creek; and the southern, of Redbank Slough. These ridges are up to 1,500 ft (457 m) wide with 20 ft (6 m) of relief. Dog Creek ridge, the longest, may be traced for over 16 mi (26 km). These ridges all trend southwest and follow converging compound fan radials. Mima mounds, of limited areal extent, are present in upper fan localities.

The surface of the Fresno compound fan is segmented (figs. 27 and 30). The upper portion averages 17 ft/mi (3.2 m/km) (0° 11′ of arc) for 10 mi (16 km), and the lower segment has a slope of 7.6 ft/mi (1.4 m/km) (0° 5′ of arc) for 13.4 mi (21.6 km). These slopes are very shallow when compared with most segmented fans (*35, 13*), which, due to their desert locales, are much steeper. The inland delta (alluvial fan) of the Kosi River, India, with a similar range front and environmental setting as the Fresno area (*21*) is also segmented, with slopes of 13.3 ft/mi (2.5 m/km) (0° 9′ of arc) for 17 mi (27 km) and 1.9 ft/mi (0.4 m/km) (0° 1′ of arc) for 79 mi (127 km).

The segmented compound fan of intermittent streams has an intersection point (of the segments) (*35*) that roughly coincides with cessation of stream incision into the fan. Above the intersection point, the major portion of the fan surface is dissected Riverbank Formation deposits with abandoned incised stream channels and swales up to 15 ft (4.6 m) deep. Below the intersection point, about halfway down the fan, the streams are now coursing on or above the average fan surface depositing Modesto Formation sediments. Some depositional ridges have 20 ft (6 m) of relief on the lower fan surface.

The segmented Fresno fans indicate tectonic displacements (*13*, *34*, *35*) with the Sierra Nevada uplifted (and tilted) relative to the subsiding San Joaquin Valley. The exact timing of the displacements cannot be determined due to a lack of age dates on the alluvial material, but the most recent is probably Late Wisconsin.

HIGH ALLUVIAL FAN OF THE KINGS RIVER

The Kings River high fan, the southernmost of the Fresno fans, is incised 20 to 30 ft (6 to 9 m). This incision has altered the high fan surface by making it considerably narrower in its upper reaches and cutting off any annual stream and sediment influx from the Kings River. The fan does display a very gentle and slightly concave radial profile with a convex cross fan profile (fig. 30, p. 35).

In the northeast and central portions of the

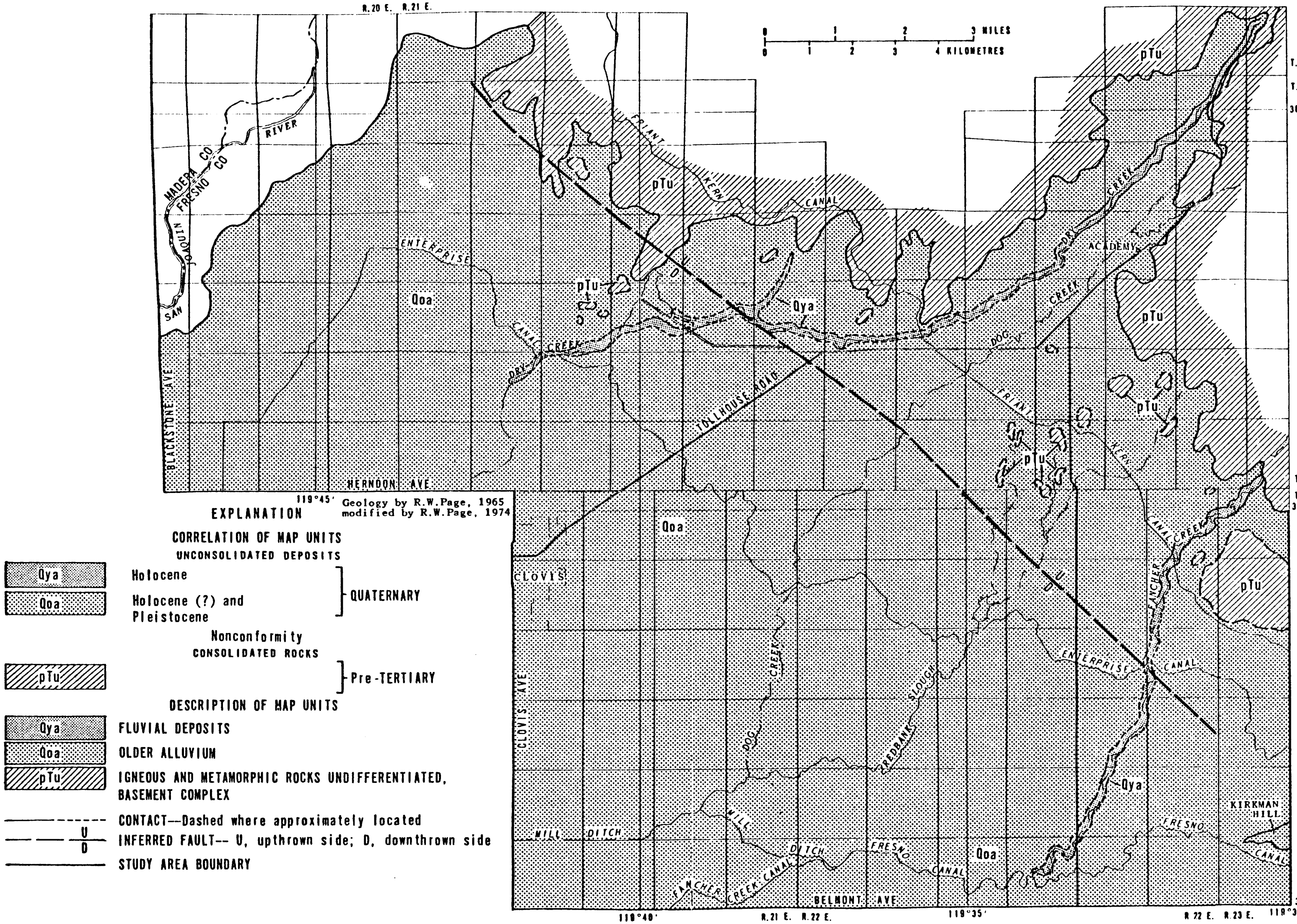


FIGURE 55.—Geologic map of the northeast Fresno area, showing the surface trace of the range front (Clovis) fault. From Page (*54*).

Kings high fan are abandoned Kings River distributary channels or splays having 10 to 15 ft (4.6 m) of relief. The channels originate near and south of Sanger and Del Rey (figs. 27 and 56) with southwest and south headings. These former water courses were apparently shallow incised channels on raised distributary deposits of the even-surfaced flood plain. The northern channel is wide with gentle banks and several major distributaries that form a complex channel pattern, whereas the central channel has few distributaries and is narrow with steep incised banks exposing Turlock Lake sediments in it. A southern channel flows south with a slightly meandering narrower discrete channel without any bifurcations. The topographic lows of the channels are now drainage and percolation ponds with little or no agriculture in the bottoms due to the poor water retention of the channel sands.

Modesto sediments west of Highway 99, in distal Kings high fan locations, have undergone extensive wind modification (fig. 57). Page and LeBlanc (*55*) identify this area as sand dunes, based on their topography, soils, and parallel alinement to the prevailing northwest-southeast wind of the area. Some of this dunal area may also be wind scour depressions with intervening ridges of undisturbed sediment on a former undulatory to level alluvial plain. Shawe (*62*) has identified wind erosion depressions in southwest Colorado that are about four times the magnitude of the Kings fan interdunal depressions. The Modesto dunes average 0.5 to 0.75 of a mi (0.8 to 1.2 km) in length, 0.125 mi (0.2 km) wide, and 5 to 15 ft (1.5 to 4.6 m) deep. In many cases, the dunes (or depressions) have rather abrupt peripheral topographic changes.

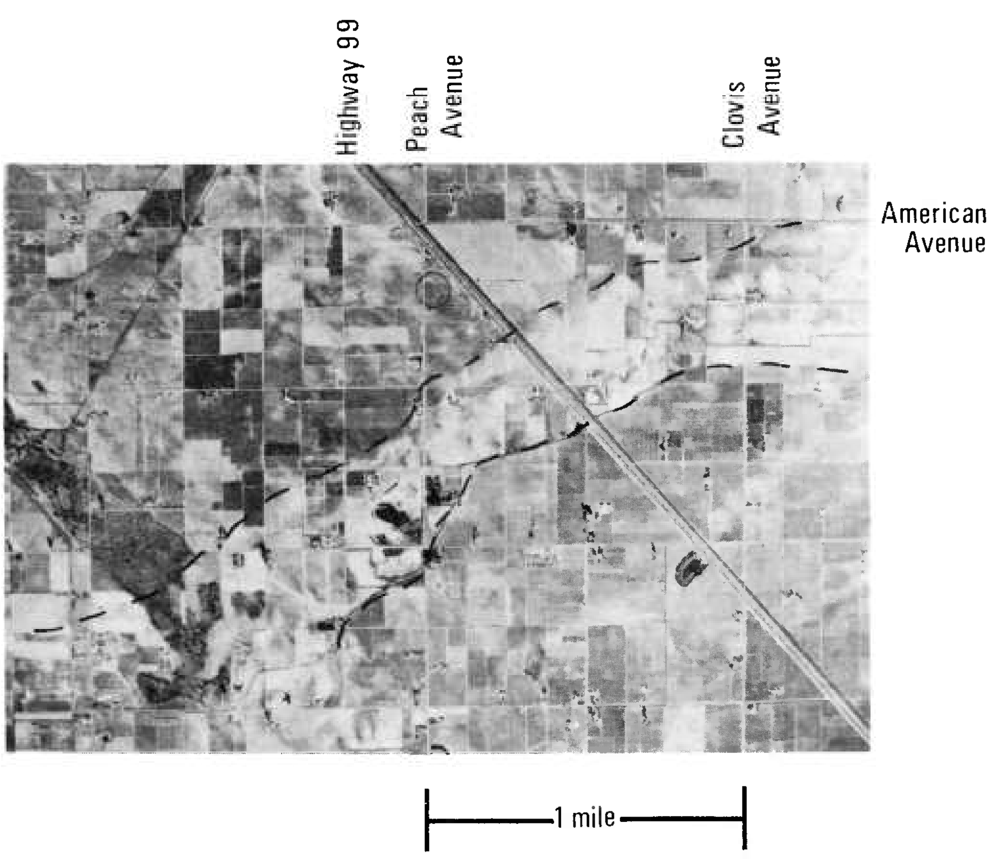


FIGURE 56.—Ancient Kings River channel south of Fresno (see figs. 27 and 52) exemplified by a shallow depression with sandy sediments.

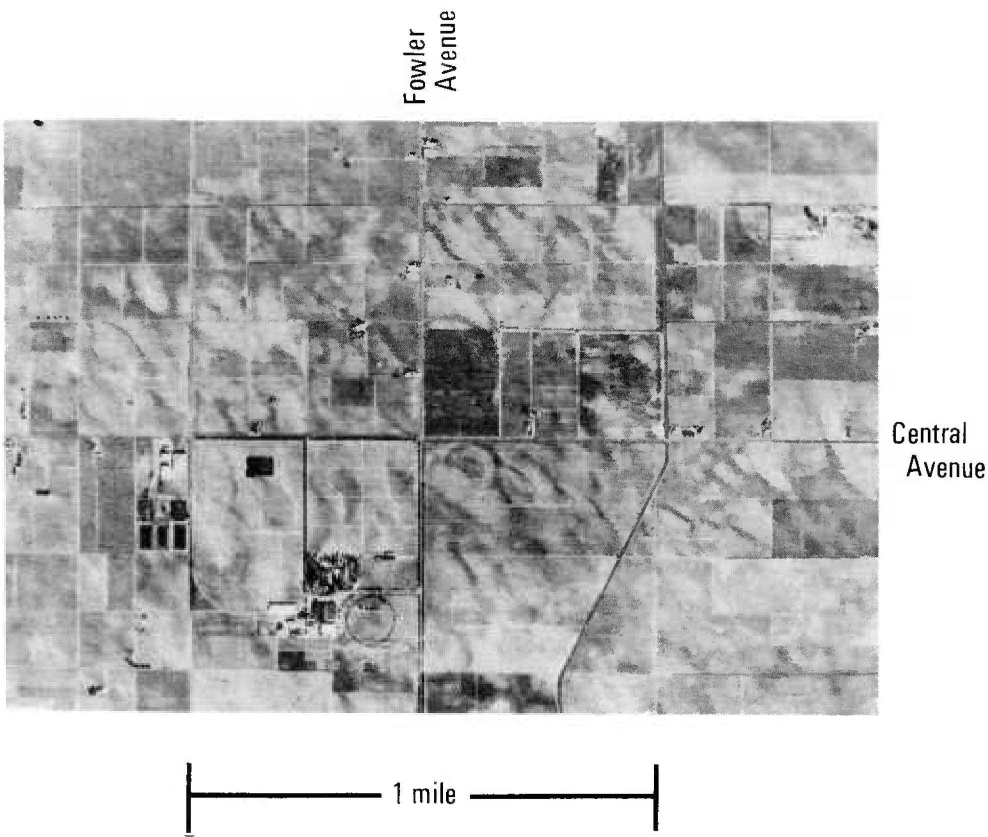


FIGURE 57.—Dunes (see fig. 27) and deflation hollows south of Fresno with the ridges parallel to the prevailing northwest winds.

DEPOSITIONAL SYSTEM VERSUS AQUIFER SYSTEM MODEL

In classic alluvial fan stratigraphy and depositional systems, coarser grained material is generally found higher on the fan, whereas finer grained materials are generally located lower on the fan. We would expect to find relatively good aquifer characteristics closer to the sediment source (that is, the mountain front) due to stream hydraulic characteristics segregating the stream's load. This does not seem to be the case for the Fresno fans, as wells drilled higher on the fans have had relatively low yields (fig. 58). To reconcile theory with the facts of poor water yielding wells in the upper fan reaches, it is necessary to evaluate the alluvial depositional system and answer the problem in light of available ground water hydrology information. The following factors are involved: (1) More fine-grained material (silt and clay) than expected is encountered higher on the fan as indicated by less than complete well log data; (2) gravels when encountered at depth (some actually cemented) yield water at less than expected quantities; and (3) the aquifer system high on the fan has lower transmissivities and storage coefficients determined from pump tests and witnessed by the lower specific capacities of wells in the area.

The Fresno fans have been segmented (*34*, *35*) by recurrent block fault uplift of the Sierra Nevada coupled with subsidence of the adjacent San Joaquin Valley. The alluvial fan deposits are deposited as sedimentary wedges onlapping and thickening from the mountain front towards the San Joaquin Valley axis where finer grain sizes predominate. As the Sierra Nevada is uplifted, the upper fan segments are elevated more

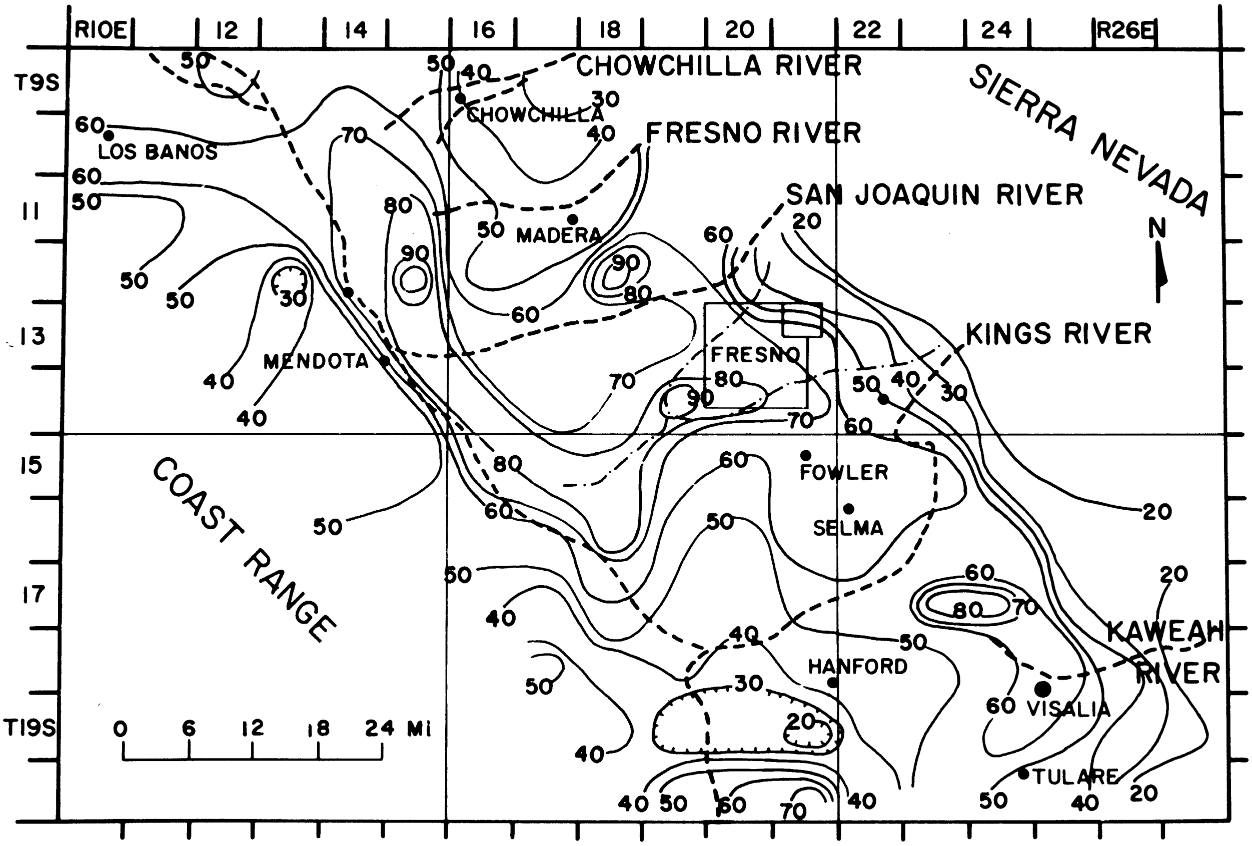


FIGURE 58.—Average specific capacities (gpm/ft of draw down) central San Joaquin Valley (*21*). The geomorphic boundaries of the Fresno area (see fig. 27) are outlined.

than the lower axial segments, resulting in stream incision at the fan head as uplift erosion outpaces deposition, whereas farther downfan, deposition will catch and ultimately exceed erosion as the streams stirve to establish grade. The Fresno fans are currently in this pregraded state, with incised or entrenched streams and rivers higher on the fans, whereas lower on the fans the water courses flow across the fan surface or are depositing topographically higher channel ridges (figs. 59 and 60). The intersection point (*34*, *35*) (fig. 59) between fan segments usually closely coincides with the change from channel incision to channel flow on or above the fan surface (see fig. 27). The lower fan segments will aggrade by stream avulsion from higher depositional ridges to intervening lows. This process eventually produces a graded fan where the upper stream reaches have filled the channel incision and now flow on the fan surface.

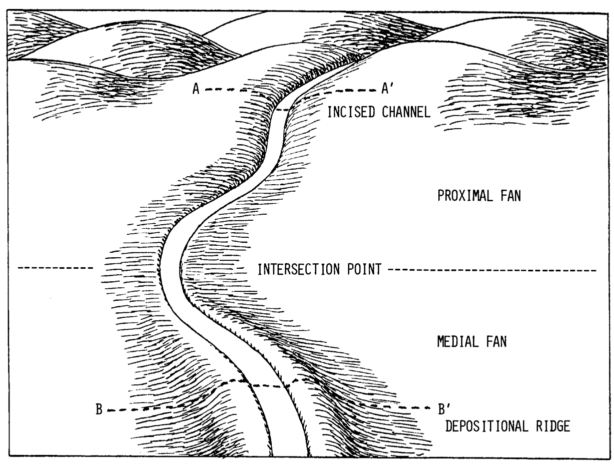


FIGURE 59.—Idealized alluvial fan topography. The stream channel is incised as it emerges from the mountain front onto the proximal fan. At some point downfan, in a medial position, the stream flows on the fan surface, whereas distally, on the fan, depositional ridges are formed by levees from stream flooding raising the streams channel above the average fan surface.

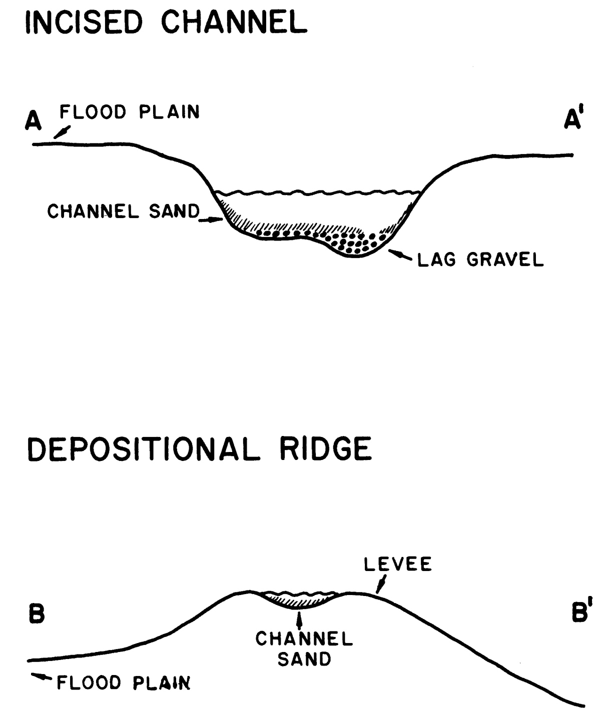


FIGURE 60.—Idealized cross section of a stream channel above (A-A') and below (B-B') the fan intersection point (fig. 59).

The sediment distribution in this depositional system follows the norm, in that the coarser material is found high on the fan and finer particles lower on the fan, but the vertical and lateral distributions are not necessarily those of a typical alluvial fan. In the areas of incision, high on the fan, the coarsest material is found as channel lag gravels and is restricted to the channel proper. During periods of flooding, only the finer material—clays, and silts, and a little sand—will crest the channel banks and be deposited on the adjacent flood plain. Thus, the coarsest material is found on the upper fan but with limited areal extent, and the largest percentage of the upper fan is covered by finer material. The gravels will also tend to silt up (*25*) as fines in the water, from either streamflow or overbank floodwater, and will settle out and fill the interstices between the gravel, cutting down the effective pore space for ground water transmission, thus making theoretically good aquifer gravels realistically poor aquifers.

Below the segmented fans intersection point, the sediment distribution will change. Here, the streams may be on or above the fan surface; the sediment load has a smaller average grain size with sand being the coarsest size available. Normally, the sand will reside in the channel bottoms (thalweg) and in point bars, but during flood stage, streams low on the fan will more easily overflow their banks by channel avulsion or crevasse splay, distributing the sand more widely. These low fan sedimentary processes form better potential aquifers having wider areal extents with well-sorted, sand-size or smaller material. The clays and silts still predominate but form discreet deposits in distal locations from the stream channel. In any vertical section through the fan (fig. 61), a greater percentage of sand will be encountered below the fan intersection point than above it. Thus, the greater thicknesses and more extensive distributions of sand lower on the fan form more extensive and continuous aquifers with better storage and transmission characteristics than those deposits higher on the fan.

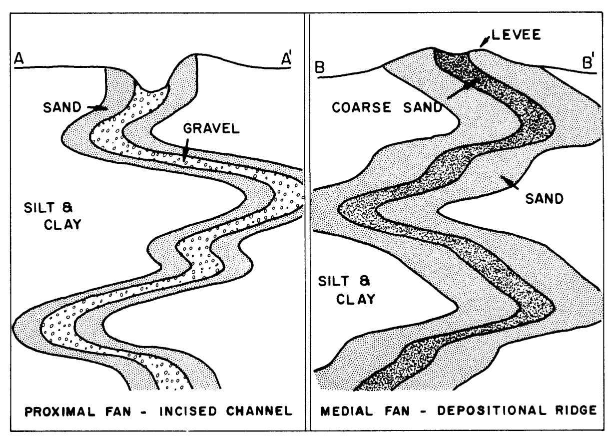


FIGURE 61.—Idealized surface and subsurface sediment distribution in the Fresno fans, showing relative distribution of aquifer material higher (A-A') and lower (B-B') on the fan (fig. 59).

HYDROLOGY OF THE FRESNO FANS

The water supply of the San Joaquin Valley is dependent upon both surface and subsurface water. The current level of irrigation and urban-industrial water use exceeds supply. The deficit is realized in the annual ground water overdraft experienced each year. All municipal and rural domestic water is pumped from the alluvial aquifers of the valley. The Fresno fans are but a small portion of the total ground water system of the valley. In the Metropolitan Fresno area, the 1977 water table was 60 to 80 ft (18 to 24 m) below ground surface, becoming shallower towards the mountain front to the east (figs. 10, 29, and 30) (Fresno Irrigation District and Bureau of Reclamation, Fresno Field Division, annual data). In this hydrologic regime, the three youngest alluvial units (Modesto, Riverbank, and Turlock Formations) contain aquifers with increasing thicknesses to the west. From Highway 99 west to the San Joaquin Valley axis, the Corcoran Clay Member of the Turlock Lake Formation separates the younger unconsolidated sedimentary fill into an upper and lower portion, which have differing water chemistries and hydraulic heads (the lower portion was originally artesian) (*20*, *21*). Within the upper Modesto and Riverbank sediments, occur vertical and lateral transmission of surface recharge water and solute dispersion from municipal and industrial wastes (*50*, *60*).

Water movement in the aquifers beneath Fresno is predominantly southwestward (fig. 10) with the water table parallel to subparallel that of the fan surface.

Figure 12 shows the areal distribution of the average ESY in the upper alluvial deposits to the north and east of Fresno from the surface to the depth of data, which ranges between 150 and 200 ft (46 and 61 m). The ESY distribution was determined by computer averaging of well drillers' logs that list only the more apparent sedimentary horizons. As defined by the California Department of Water Resources (*16*), the drillers' well log descriptions are equated to ESY values as follows:

Well log call	*Percentage of estimated specific yield*
Crystalline bedrock	0
Clay and shale	3
Clayey sand and silt	5
Cemented or tight sand or gravel	10
Gravel and boulders	15
Fine sand	15
Sand and gravel	20
Coarse sand and fine gravel	25

The ESY theoretically indicates the percentage of water yielded from a unit volume of aquifer, but it also gives a general indication of the type of sediment encounterd (coarse or fine) and its general aquifer characteristics (for example, good or poor transmissivities).

The western portion of figure 12 has higher ESY's, reflecting the coarser aquifer material deposited by the southward shifts of the San Joaquin River channel during the Pleistocene. The isolated high ESY's to the east delineate coarser stream channel deposits of the smaller ephemeral streams crossing the compound alluvial fan. This knowledge of areas with higher inferred transmissivities (from the ESY's) and coarser stream deposits is of significant value when considering distribution and dispersal of suburban and industrial waste, placement of artificial recharge basins and wells, and potential water well sites that would have higher yields.

Horizontal water movement in these coarser stream sediments has been observed to approach 0.61 ft/day (0.19 m/day) by Nightingale (personal commun.). This is a tracer velocity from a surficial gypsum ($CaSO_4$) application, and its measured advance is in the shallowest aquifers beneath an artificial recharge basin. The hydraulic gradient was that associated with the recharge mound. In the Fresno area, aquifers in the three upper alluvial formations, both above and below the water table, are apparently bounded by confining layers. Both well tests and piezometric observations during recharge at

Leaky Acres indicate these aquifers function as semiconfined aquifers and percolate (leak) vertically through a confining layer to other lower semiconfined aquifers. Aquifer tests in the Fresno area (*40*) and unpublished data of the authors) yield storage coefficients that fall within the realm of artesian aquifers (0.00018 to 0.003) (*26*). These coefficients confirm the semiconfined nature of the artesian aquifers.

Some alluvial deposits in the Fresno fans form better aquifers than others. The best yielding aquifers appear to be channel lag, levee, and crevasse splay deposits. The channel lags are coarser grained with very good porosities and permeabilities. Proximal surficial crevasse splay deposits have moderate sorting and chaotic massive bedding, yielding reasonably large permeabilities. The levee deposits vary as to their aquifer characteristics; some (fig. 54) have very poor sorting and massive bedding, principally those in the Modesto and Riverbank Formations, whereas the Turlock Lake levee deposits have better sorting but still show massive bedding. The Modesto and Riverbank levee deposits are good-to-fair aquifers, whereas the Turlock Lake levees are fair-to-poor aquifers.

According to the literature (*1*, *2*), point bar deposits are potentially good aquifers, but in the Fresno fans they are finer grained and fairly well sorted with adequate porosity; yet on the whole, they are only fair aquifers. The Fresno flood plain clays are very fine, well-sorted deposits and are identified with confining beds for vertical movement of water.

These deposits have different length-to-width ratios. Their long dimensions orient from north to south in proximal San Joaquin River material, to northeast to southwest for the compound fan deposits and the more distal San Joaquin and Kings River deposits, to east to west for a few Kings River derived deposits.

The grain sizes found in one deposit type will also vary with distance from the source area because transport abrasion and weathering, along with decreasing stream discharges and velocities, will deposit the coarsest material high on the coalescing fans, whereas finer material is encountered in medial and distal locations. In the Fresno fans, another factor is involved. In proximal fan locations closer to the Sierras, the coarsest material is restricted to narrow channel deposits with the great percentage of the total area consisting of overbank fines, limiting the influence of the coarsest stream material.

Formational Geology as Related to its Geohydrologic Function in a Ground Water Flow Regime

MODESTO FORMATION

Modesto Formation sediments, the youngest, most extensive surficial deposits on the coalescing Fresno fans, are located in more distal fan positions. Centrally located surficial sediments display a large number of crevasse splay, levee, and channel meander deposits. These are coarser grained sandy deposits formed by a heterogeneous mix of alluvium with good porosities and permeabilities, higher transmissivities, and no confining beds.

Southwest, toward the San Joaquin Valley axial trough, are more flood plain deposits with greatly reduced permeabilities. Among these flood plain clays and silts are channel deposits and ridges with better permeabilities and higher transmissivities. Figure 11 shows the correlation of high chlorides (*60*) to the surficial stream channel deposits (associated with Dry and Dog Creeks, Redbank Slough, and San Joaquin distributary deposits) in the Fresno Sewage Treatment Plant area (*17*). The high chloride lobes are correlative with the relatively coarser stream channel deposits, having greater transmissivity than the intervening flood plain clays, which act as confining beds. The chloride lobes do not show the effects of dilution but, rather, the greatly different transmissivity of the stream channel fine silty sands and the flood plain clays.

Thus, the Modesto Formation shows good vertical and horizontal permeabilities and transmissivities in midfan positions, which decrease downslope as finer sediments, principally flood plain deposits, are encountered farther from the source area.

RIVERBANK FORMATION

The Riverbank Formation is exposed higher on the coalescing Fresno fans. It is very similar hydraulically to the Modesto Formation because of its similar sedimentology. There is one basic and hydraulically important difference. A paleosol (*39*) (ancient soil) forms the upper surface of the Riverbank Formation and is the first aquitard encountered. In some localities, it is an iron-silica cemented hardpan (*37*), specifically where the San Joaquin soil series is encountered surficially or subsurface beneath the Modesto cover.

The Riverbank hardpan and nonhardpan paleosol act as a confining bed for any vertical movement of recharge water; it is generally the first confining bed encountered higher on the coalescing alluvial fans. Figures 6 and 62 demonstrate how these beds react under the Leaky Acres Recharge Facility of the city of Fresno (*50*) (fig. 33). The perching that occurs on layers from 14 to 38 ft (4.3 to 11.6 m) was measured with piezometers. Recharged water rapidly fills the more permeable sediments between the layers, but once the upper sedimentary column is saturated above succeeding confining beds, there is very little head loss across the hardpan layer at 14 ft (4.3 m) and vertical flow is controlled at the 38-ft (11.6 m) depth.

The Riverbank, like the Modesto, is a heterogeneous sedimentary unit. High on the fan surfaces are many good aquifer deposits, such as crevasse splays, levees, and channel deposits with higher transmissivities and porosities. Greater amounts of flood plain and finer grained levee and distributary deposits on distal portions of the fan may act as confining beds.

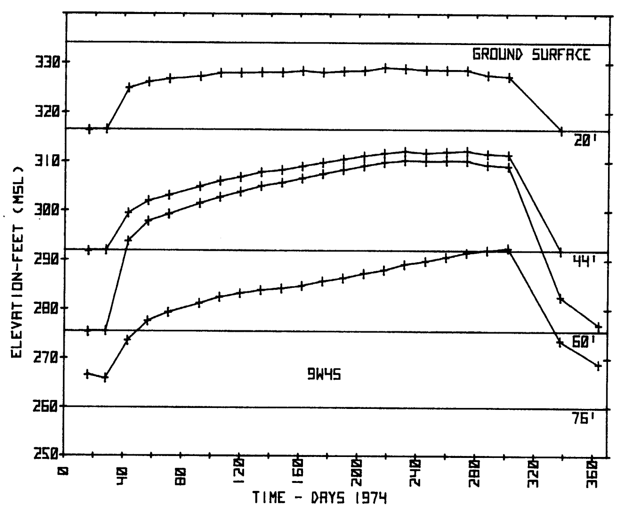


FIGURE 62.—Four piezometric surfaces located at 9W1S beneath the Leaky Acres Recharge Facility are shown. Recharge water was applied from Jan. 16 to Nov. 1 (289 days). Head losses between piezometers are indicative of perching beneath the recharge site, the leaky aquicludes, and the semiconfined aquifer.

TURLOCK LAKE FORMATION

The Turlock Lake Formation, when considered aerially and vertically, is the principle aquifer beneath the Fresno fans. The cities of Fresno and Clovis derive all the municipal water from this formation.

The lithologic cross section shown in figure 5 (p. 7) is derived from the network of observation wells located at the city of Fresno's Leaky Acres Recharge Facility (*51*). The cross section is based on sieved and hydrometer soil classifications (*48*) and gives an indication of the great variety and variability within the Turlock Lake Formation. (See fig. 33 for location of cross section.) The Riverbank-Turlock Lake contact is encountered at 35 to 40 ft (10.7 to 12.2 m) in this locale and is defined by the appearance of flood plain clays. This uppermost clay acts as a confining bed, which develops a semiperched aquifer above it with a 20- to 25-ft (6 to 7.6 m) head loss across it (figs. 6 and 62). Another confining bed (fig. 5) is encountered at approximately 60 ft (18 m). It, too, develops a semiperched aquifer above it with a 15- to 20-ft (4.6 to 6 m) head loss.

The Turlock Lake Formation is a sedimentary sequence with a variety of depositional environments represented. The flood plain clays above the current water table act as confining beds, which may develop semiperched water tables in the aquifers above them if recharged naturally or artificially with good waters (low in pollutants, turbidity, and sediments) or industrial and municipal waste (*17*, *60*). Once the water table (zone of saturation) is encountered, the direction of water movement will become nearly horizontal. In this regime of saturation, the clays still operate as hydraulic confining beds, the higher volume and velocity of water movement being in the beds with greater transmissivities—channel lags, crevasse splays, and some levee and point bar deposits.

The Turlock Lake Formation is a good aquifer with much potential for ground water storage and yield; however, because of its horizontal and vertical sedimentary variability, some horizons and specific areas, such as the paleochannel deposits, will have greater transmissivities than others. Identification of ancient stream channels (*28*) with subsequent location of wells in and near them will yield more water per unit of energy. Reversing the process, better sites for recharge would be located in areas of these ancient channels.

Another factor involved in the aquifer's operational performance is the location and amount of recharge available. A very small portion of the natural recharge is derived from rainfall directly on the fans and only slightly more from intermittent runoff from watersheds feeding the interfan streams. Evidence now indicates that a significant part of all recharge is derived from agricultural overapplication of water (*29*) (incidental recharge) with both natural and incidental recharge increasing away from the mountain front. Combining the downfan water volume increase with the fact that aquifer characteristics (sedimentologically) become better farther downfan, it is evident why there is a downfan increase in the yields, transmissivities, and storage capacities of the aquifers. This is substantiated by the better specific yields of Fresno city wells in midfan localities over those closer to the Sierras.

Computer synthesized data of well logs show that the greatest influence on the sedimentation in the Fresno area is the San Joaquin River, which has shifted position through the Pleistocene. At one time, it flowed south through the area on which Fresno is built today. There is less Kings River influence due to its distance from the city's locale. Both of these major rivers have supplied large quantities of sedimentary material of coarser average grain size to the fans strata, as indicated by computerized ESY data, indicating better water transmitting capacities. The intermittent streams, while building their own fan, have neither the volumes, velocities, nor the drainage basin to input as much coarse-grained material to the fan system. They do deposit some coarse-grained material, but when comparing these intermittent stream deposits with those of the major rivers they are insignificant in size, volume, and extent of better aquifer material and continuity of the aquifers. Thus, Turlock Lake Formation sedimentary deposits derived from the major rivers offer better water use potential for both recharge and extraction.

Hydraulic Summary

The three significant formations of the Fresno fans have varying hydraulic properties. The Modesto and Riverbank Formations, because of their greater grain size heterogeneity and thicker bedding, have very good porosities and transmissivities, which decrease towards the San Joaquin Valley trough as the grain size decreases and grain size homogeneity increases. The underlying Turlock Lake Formation today contains the major aquifers of the fan. Because of its greater heterogeneity between beds and thinner bedding with good internal grain size homogeneity, it has variable transmissivities, which depend upon (1) the type of sedimentary deposits, (2) the lateral distribution of these deposits, and (3) the frequency of occurrence and the total thickness of a particular deposit type at that location. Thus, the Turlock Lake has reduced vertical permeabilities because of the number of confining flood plain deposits, but good horizontal transmissivities are found within the coarser units.

These alluvial deposits, in conjunction with the present availability of recharge water from natural, artificial (surface spreading), and incidental overirrigation, form excellent aquifers yielding immense quantities of water.

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